BSM at future colliders (with a focus on dark matter)

Caterina Doglioni - University of Manchester & Lund University

@catdoglund, she/her

Outline

- Quick introduction to questions & tools
- Do we even need to have SM problems to look for BSM?
- SM problems we may have
- SM problems we definitely have
  - In particular, dark matter (and some experimental considerations)
  - Synergies with complementary experiments
- Conclusions

Disclaimer #1: This is not an exhaustive talk on all BSM physics that has ever/ will ever be searched for
Inclusions (and omissions) are a matter of personal taste, especially because I *really like hadronic jets*
Disclaimer #2: I conveniently pillaged the **Snowmass Energy Frontier Restart Workshop** from last week
(if you have questions about Snowmass OR would like to see your studies included in it, let me know!)

Quick introduction

The landscape of future colliders

- See S. Gibson's slides on Monday for further information on technologies and timelines

e+e- colliders

Collider	Geometry	$\sqrt{s}$ [GeV]	$\mathcal{L}_{inst}$/Det. [10^{34}cm^{-2}s^{-1}]	Time [years]	$\mathcal{L}$ [ab^{-1}]
FCC-ee	Circular	91	100–200	4	150
		161	25	1–2	10
		240	7	3	5
		365	0.8–1.4	5	1.5
CEPC	Circular	91	17–32	2	16
		161	10	1	2.6
		240	3	7	5.6
ILC	Linear	250	1.35–2.7	11.5	2
		350	1.6	1	0.2
		500	1.8–3.6	8.5	4
CLIC	Linear	380	1.5	8	1
		1500	3.7	7	2.5
		3000	6	8	5

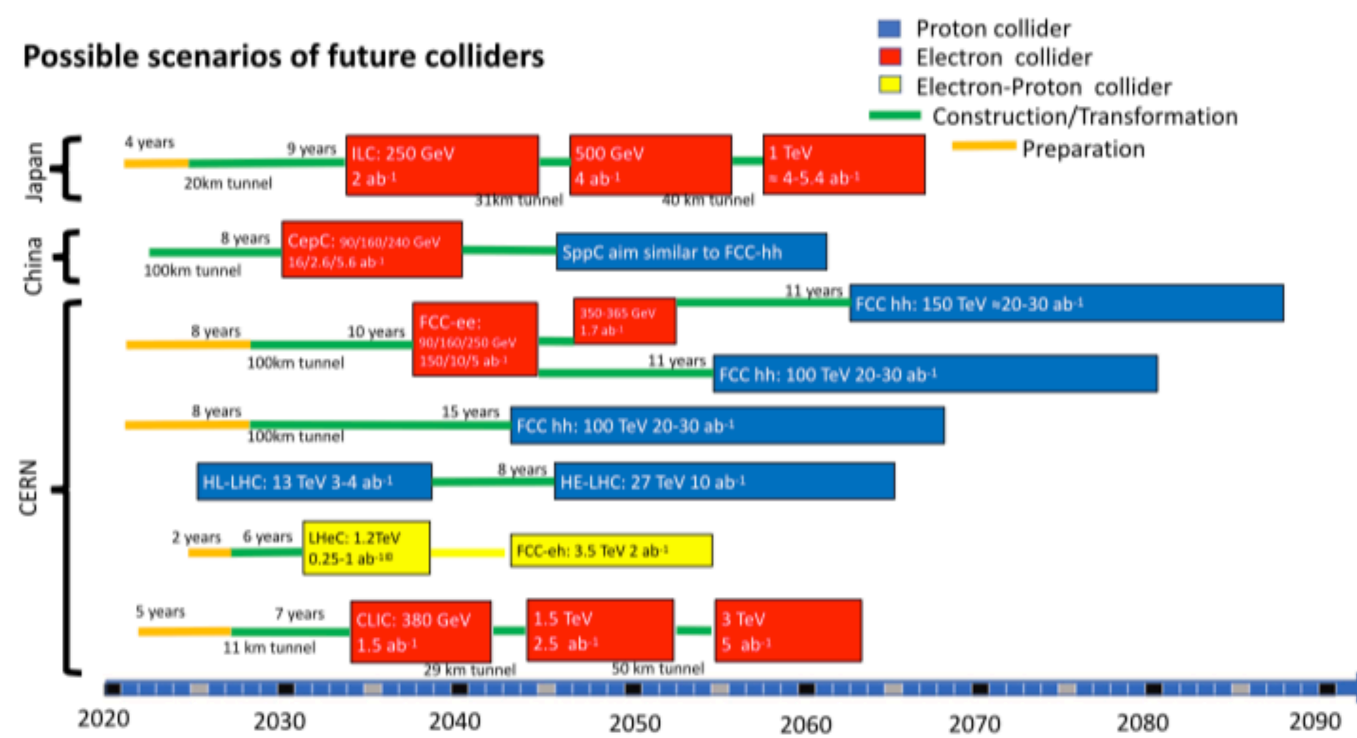
pp colliders

Collider	$\sqrt{s}$ [TeV]	$\mathcal{L}_{inst}$/Det. [10^{34} cm^{-2}s^{-1}]	Time [years]	$\mathcal{L}$ [ab^{-1}]
HL-LHC	14	5	12	3
HE-LHC	27	16	20	15
FCC-hh	100	20–30	25	20
LE-FCC	37.5	–	–	10

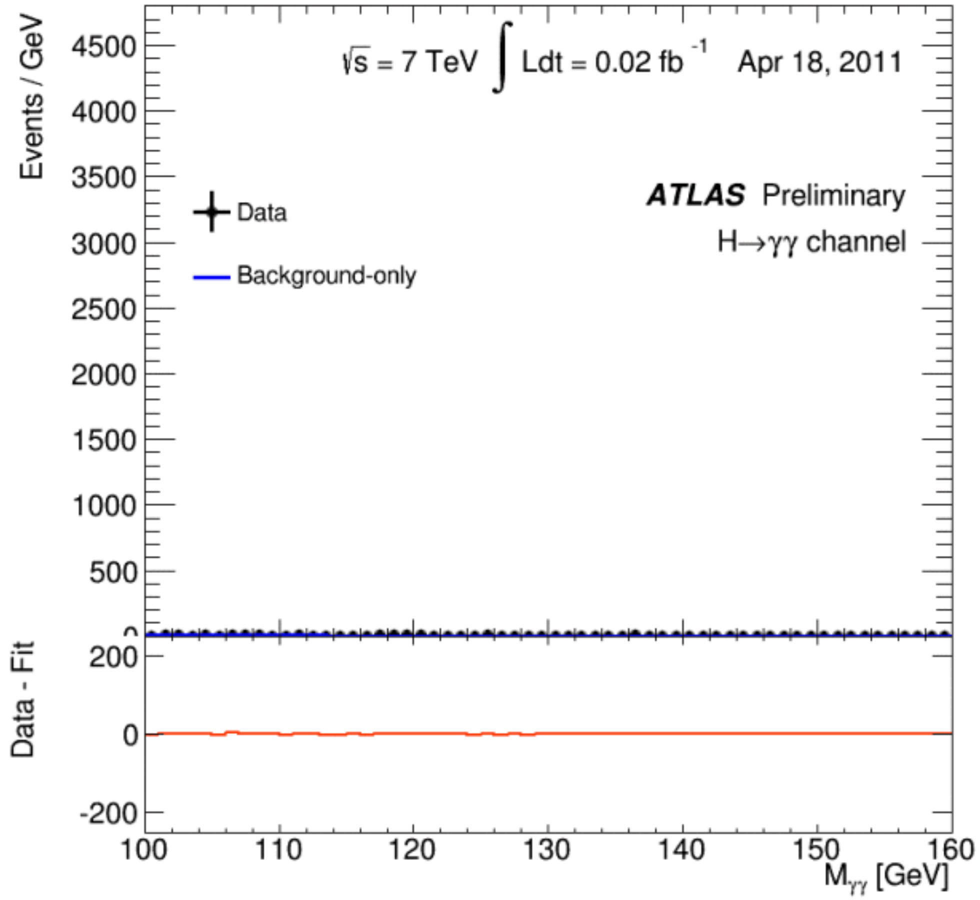
H. Gray, Reviews in Physics 6 (2021) 100053

muon colliders

Collider: muon collider
Geometry: circular
CoM energy: 3-30 TeV
Instantaneous luminosity:
Time [years]: ??
Integrated luminosity: up to 2/ab



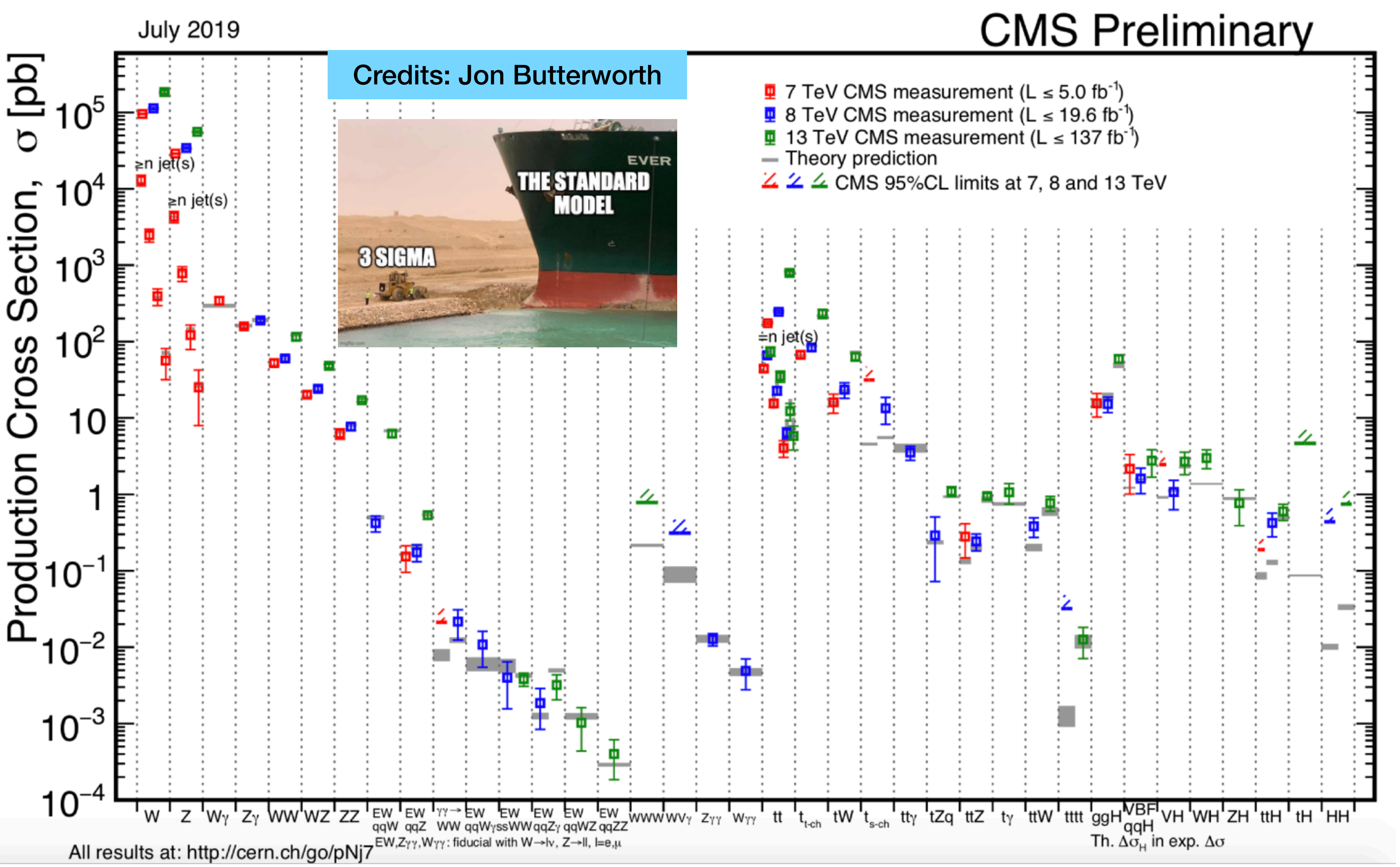
What does it take for a BSM discovery?



- A particle **collider** (LHC)
  - Many collisions/second
  - Only one in 10^{13} may contain an interesting event (e.g. Higgs boson)
- **Detectors** able to select and precisely measure particles (photons)
  - Millions of read-out channels
- Many **experimental teams** that:
  - Operate the detector
  - Reconstruct and calibrate particles
  - Do the data analysis
- **Theory community** that (among other things):
  - Provides precise background predictions

- Current high energy colliders: **LHC** (HL-LHC is a present-to-future collider)
- Future colliders are still prospective studies → the above cannot yet be taken for granted! *this is an interesting topic for discussion…*
- **Consequence:** not every future collider study has a comparable level of "robustness"
  - Most studies make *reasonable* assumptions
  - Note also that theory/experiment thresholds of *reasonable* vary

The landscape, as seen from current colliders



Watchlist (incomplete / in no particular order):

- LHCb/Belle's lepton flavor universality results
  - see J. Harz's talk on Monday
  - see A. Tricoli's Snowmass talk
- Muon g-2
  - see talk on theoretical developments this morning
- Gravitational wave signals
  - one among many examples of possible interesting collider signatures in certain model
- The occasional LHC excess
  - A provocative paper: arXiv:1209.3522

In any case, a **very different situation** with respect to LHC restart in 2010!

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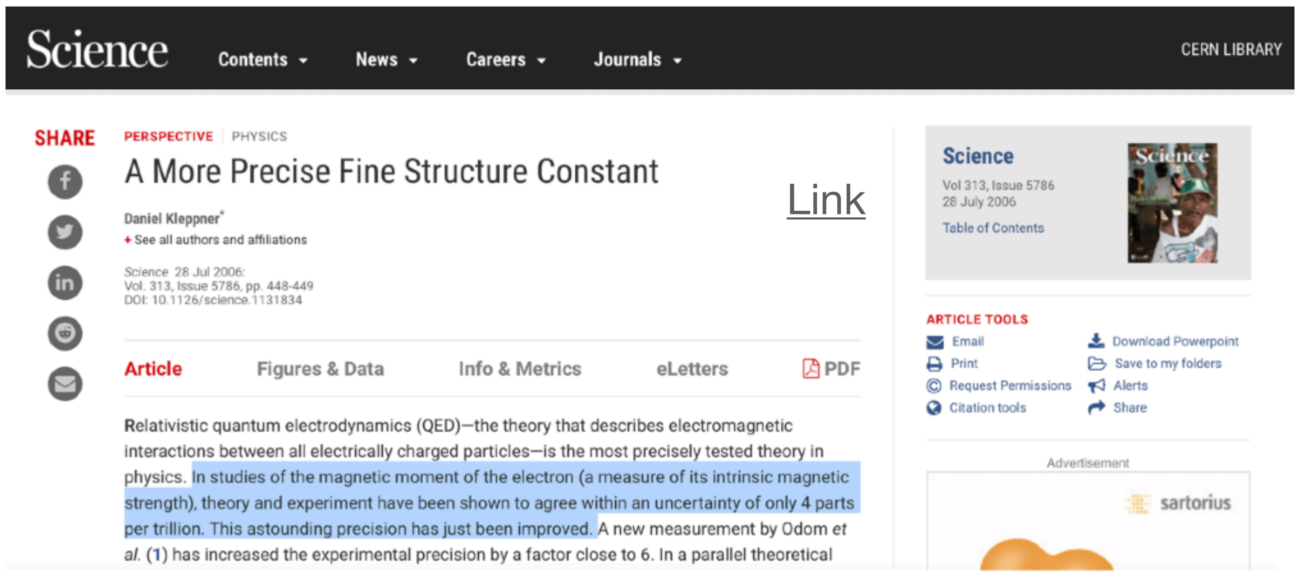
So, why keep measuring & looking for new physics?

Reason #1 (of many): extending our understanding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A More Precise Fine Structure Constant

Link

Daniel Kleppner*

+ See all authors and affiliations

Science 28 Jul 2006:
Vol. 313, Issue 5786, pp. 448-449
DOI: 10.1126/science.1131834

Article | Figures & Data | Info & Metrics | eLetters | PDF

Relativistic quantum electrodynamics (QED)—the theory that describes electromagnetic interactions between all electrically charged particles—is the most precisely tested theory in physics. In studies of the magnetic moment of the electron (a measure of its intrinsic magnetic strength), theory and experiment have been shown to agree within an uncertainty of only 4 parts per trillion. This astounding precision has just been improved. A new measurement by Odom et al. (1) has increased the experimental precision by a factor close to 6. In a parallel theoretical

Science
Vol 313, Issue 5786
28 July 2006
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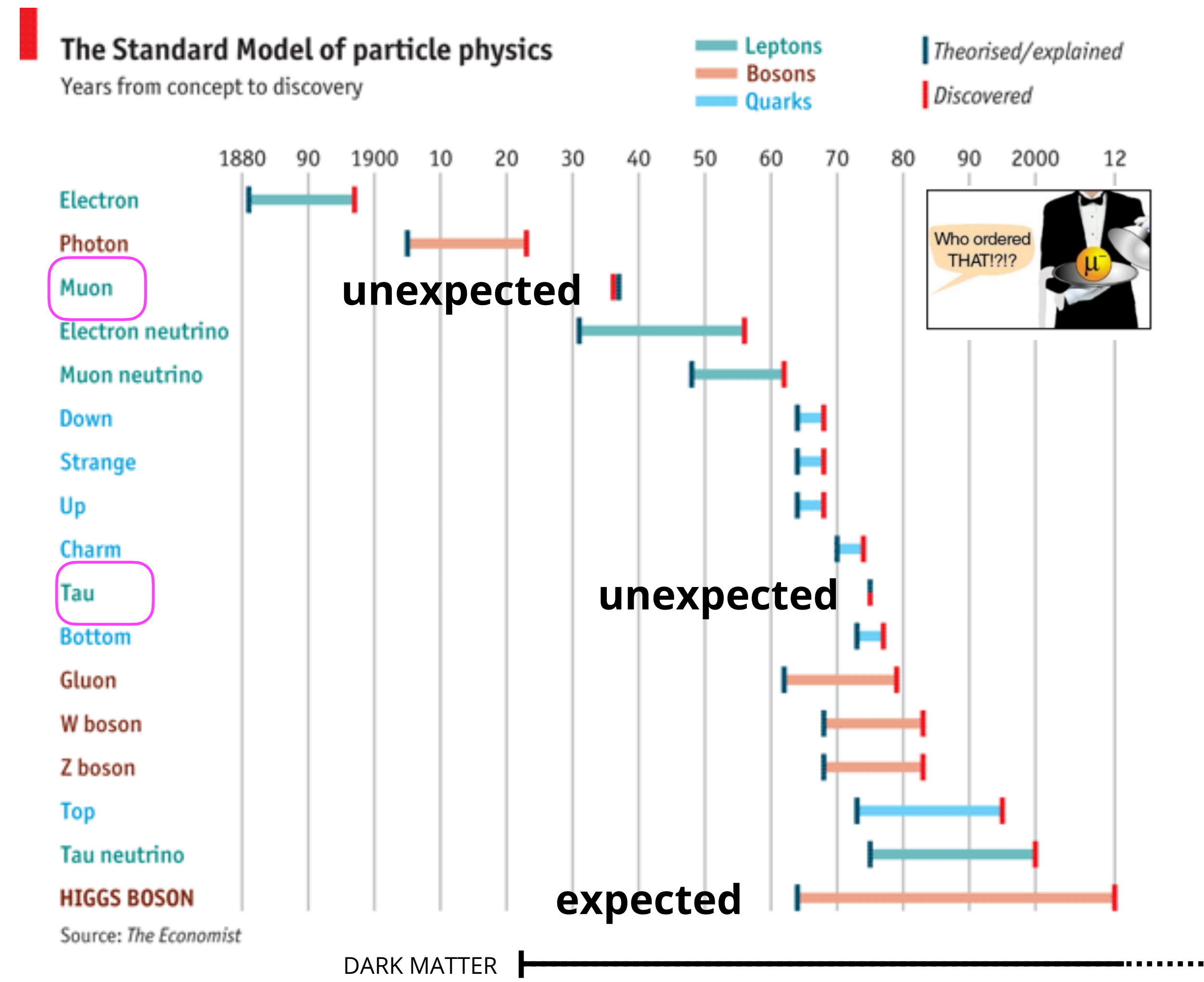
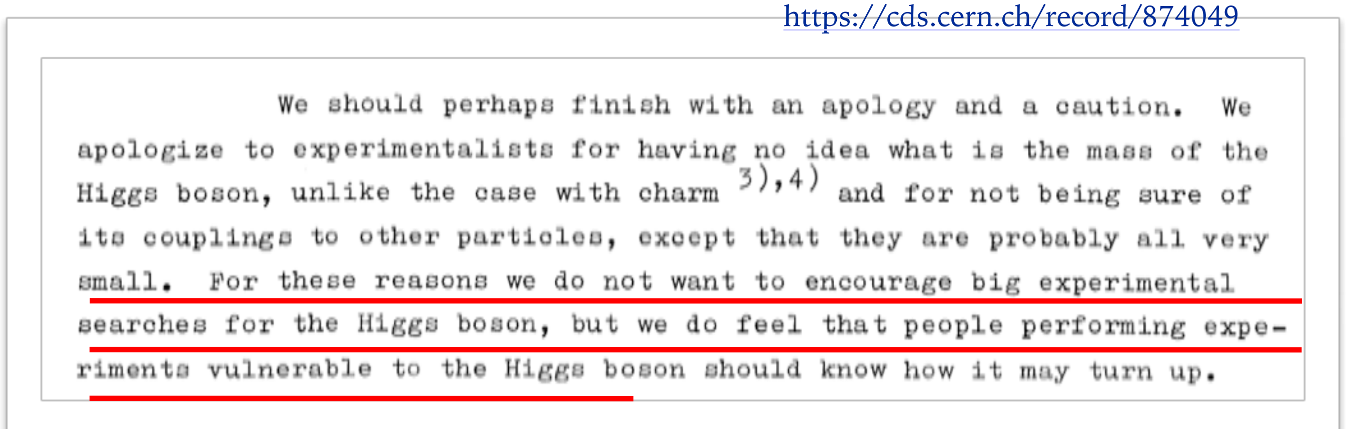
Reason #2: unexpected discoveries



The Economist

[Historical] reason #3: stubbornness

https://cds.cern.ch/record/874049


We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm 3),4) and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

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…we don’t need any SM problems to look for BSM!

Do we need any problems of the SM to look for BSM?

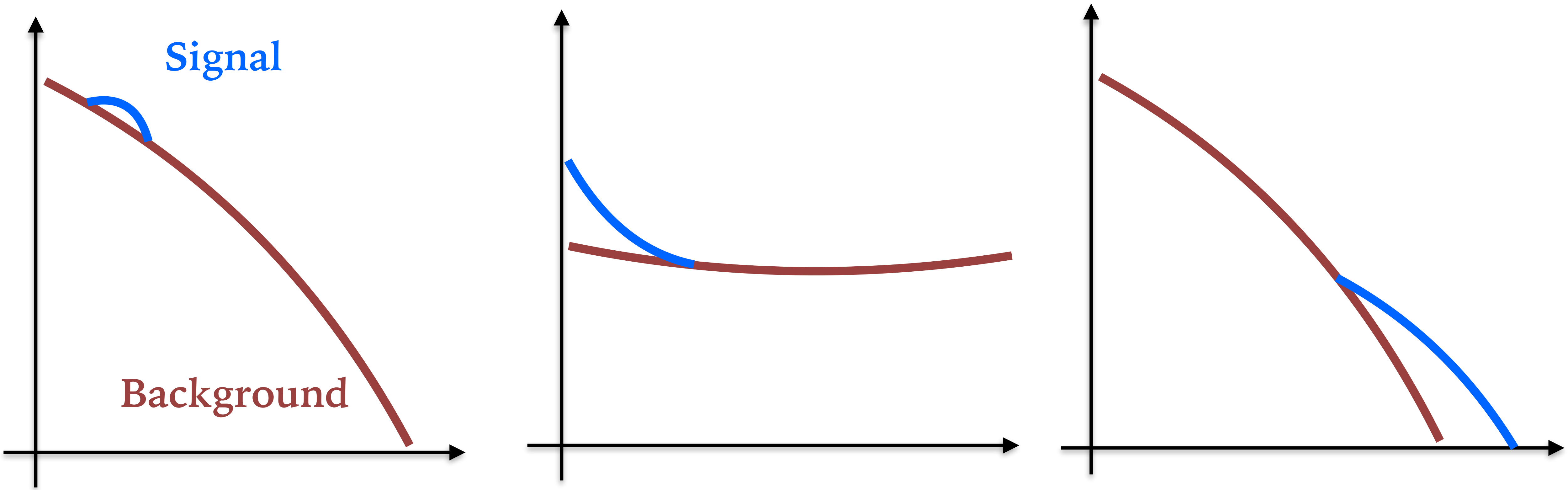
- see also intro message from Daniel De Florien's talk yesterday

The SM has no problems (according to LHC measurements so far)!
- Measurements so far agree with theory

✅Energy frontier => direct exploration of the unknown
"Generic" ***direct search strategies***:
look for (sizeable) deviations signalling the presence of new particles
Examples of bread-and-butter (is this really true?) search: dijet at future colliders

❌Energy frontier => it'll be a while before a big increase in center of mass energy
Indirect search strategies:
look for (small) deviations from the presence of new particles in loops
Examples of flavor physics searches at future colliders
(but mostly leaving this to other talks in this conference)

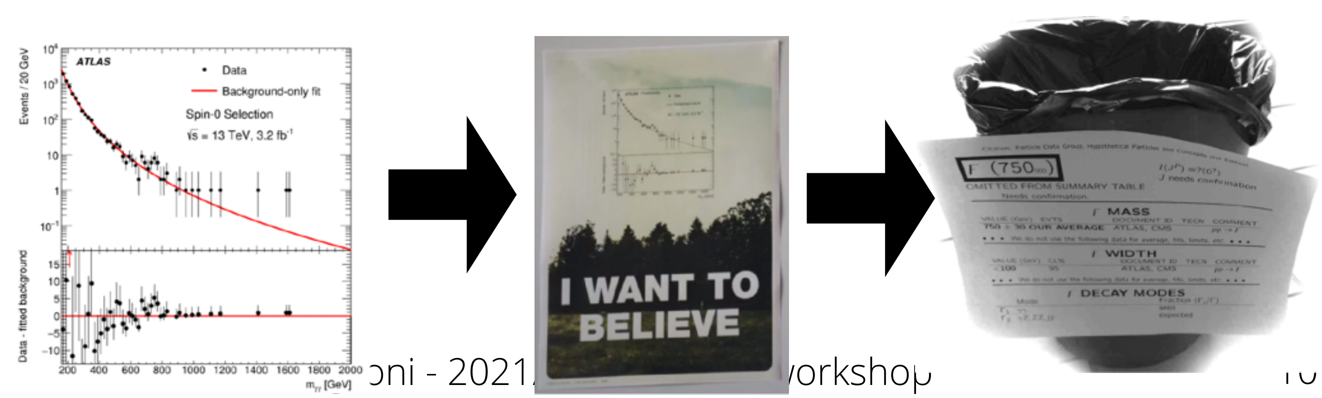
“Direct” collider manifestation of new phenomena



These are just **examples** of distributions analysed in searches at ATLAS and CMS

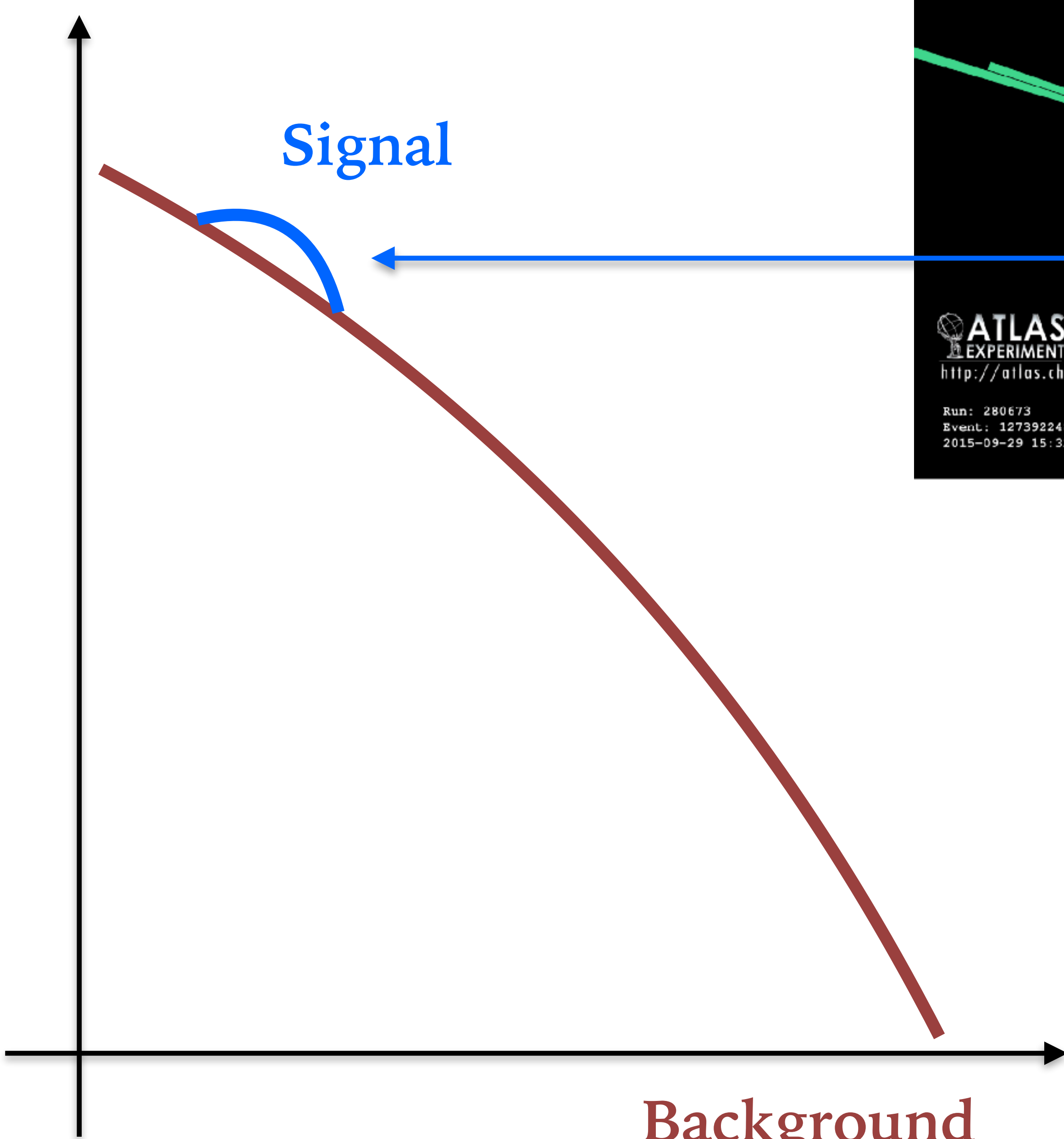
Ingredients: data, background prediction, statistical analysis

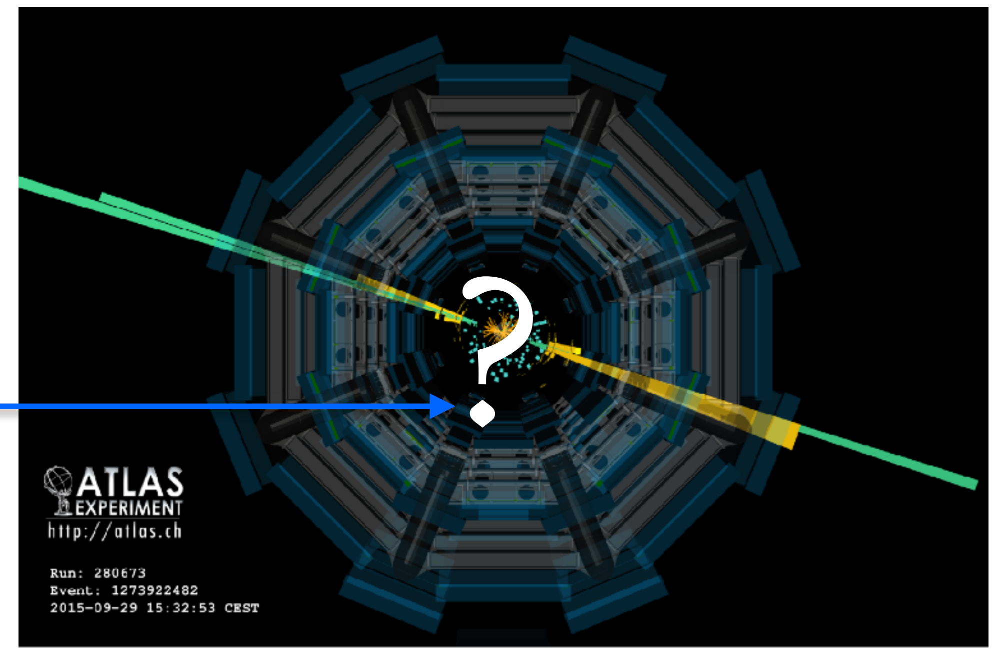
...will focus on the first two, but the third one is not trivial either:

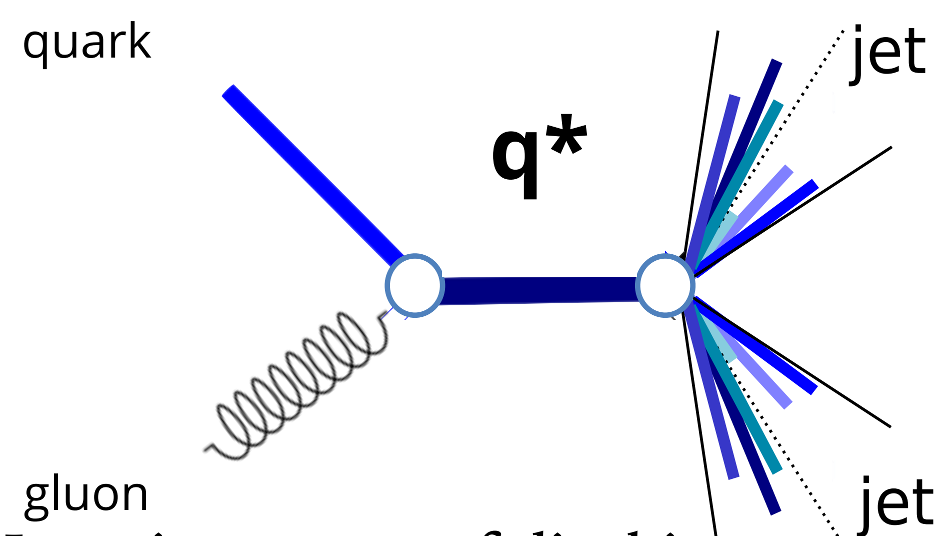


A classic: searching for resonant excesses (the BumpHunt ™)

Number of events



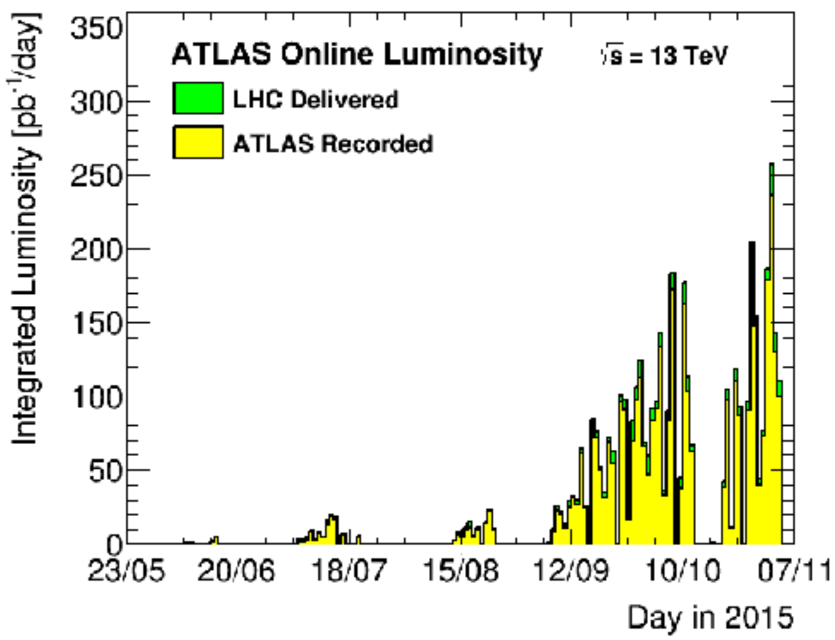




Invariant mass of di-object system
(~new particle mass)

How keen are experimentalists to do these searches?

Very! 1 month after first Run-2 data...



Submission history

From: Atlas Publications [view email]

[v1] Fri, 4 Dec 2015 20:15:47 GMT (778kb,D)

https://arxiv.org/abs/1512.01530

Submission history

From: The CMS Collaboration [view email]

[v1] Thu, 3 Dec 2015 20:49:43 GMT (1357kb,D)

http://arxiv.org/abs/1512.01224

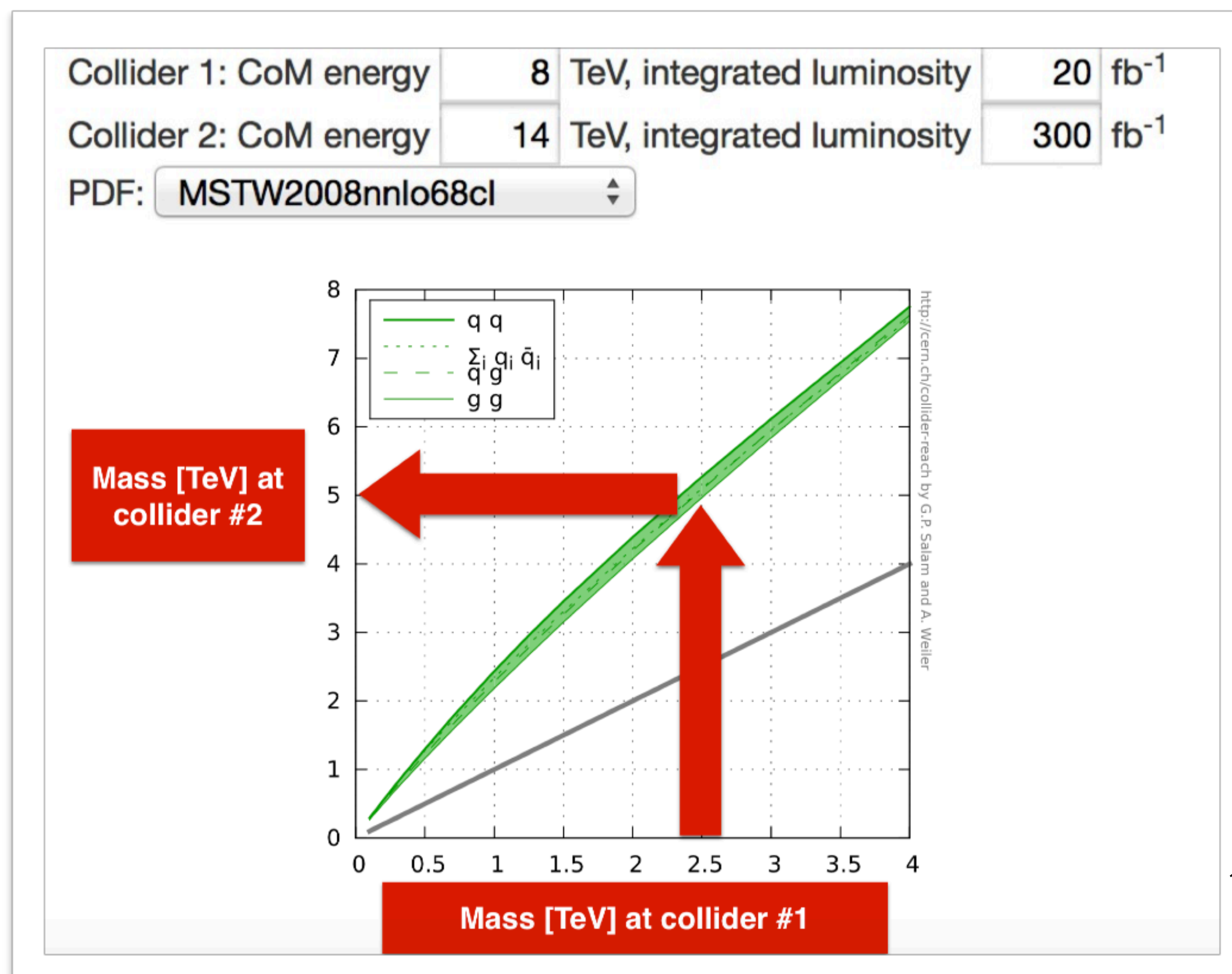
Increase in LHC energy

⇩

Greater discovery potential for new high-mass states

Details in G. Salam's talk on Collider Reach tools

Try it yourself at http://collider-reach.web.cern.ch/collider-reach/



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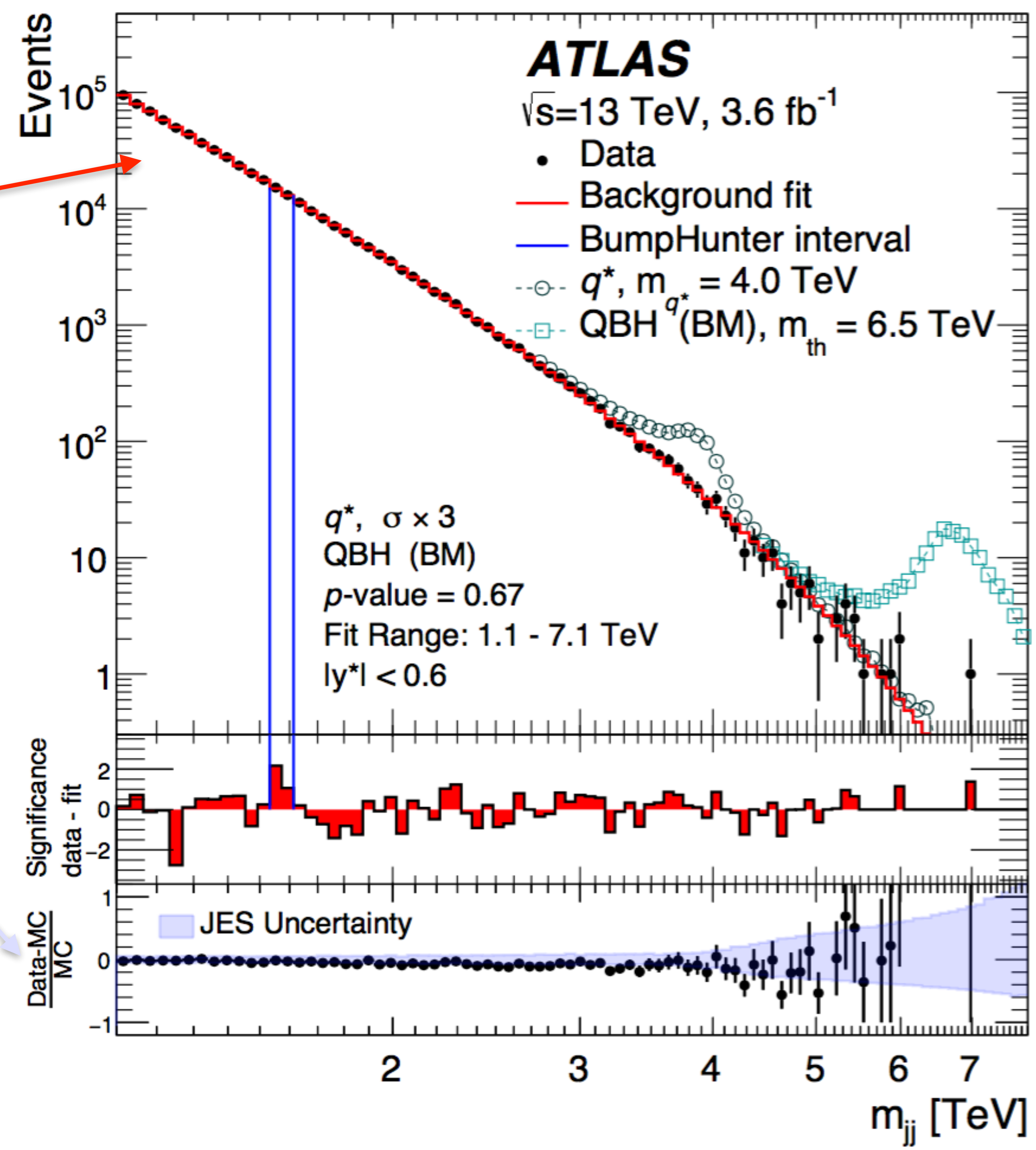
Is hunting bumps enough?

Simplest way: compare **data** with **smooth QCD-inspired fit, e.g.:**



Compare **data** with **simulation** (Pythia), but mostly as a cross-check

Is hunting bumps enough? No.

Simplest way: compare **data** with **smooth QCD-inspired fit**

Pitfalls

1. High-rate process data not always available, there is too much of it (see later for details)
2. *Smoothness* is a valid assumption only up to a point, because:
   [We're already having this problem at the LHC]
   1. Calibration effects, including jet (q/g) flavour effects
   2. We actually don't know if QCD is smooth at all orders

Compare **data** with **simulation** (Pythia), but mostly as a cross-check

Solutions?

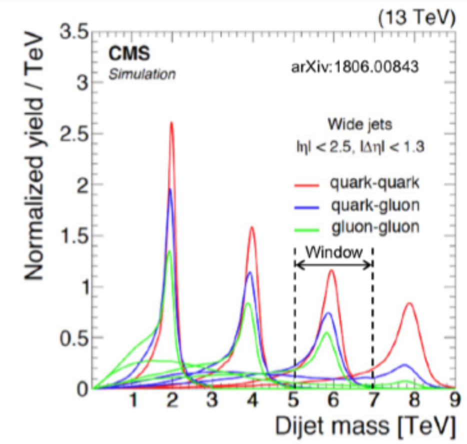
1. Use non-standard data-taking workflows (see later)
2. Use hybrid fit/NLO bkg methods from control regions
   - Already used by CMS, improves on sensitivity
3. Use full comparisons of data to NLO
   - Done at the LHC for e.g. chi distribution
   - Potentially limited by theory precision
   - Theory/experiment dialogue on fiducial cuts needed

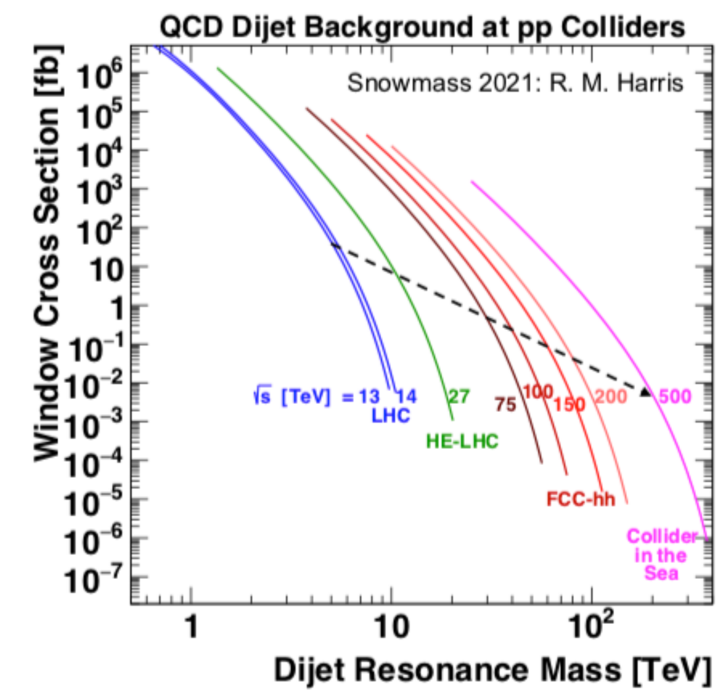
Under ideal conditions...

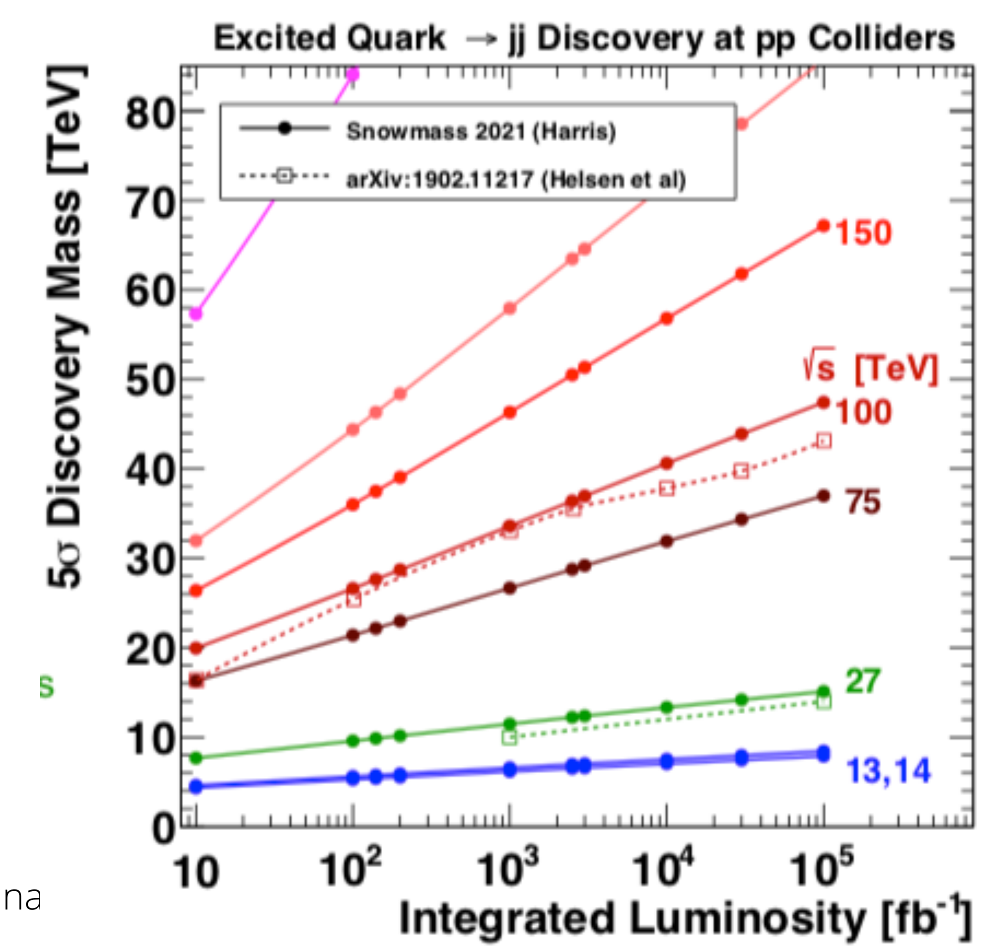
Energy Frontier Restart Workshop, September 2021

R. Harris, Talk at Energy Frontier Restart Workshop

- $\sqrt{s}$: eight collision energies
  - LHC & HL-LHC: 13 & 14 TeV
  - HE–LHC: 27 TeV
  - FCC–hh: 75, 100 (default), 150, 200 TeV
  - Collider in the sea: 500 TeV (why not . . .)
- $\int \mathcal{L}\, dt$: ten integrated luminosities
  - Five general values with logarithmic spacing: $10^1 - 10^5$ fb^{-1}
  - Five benchmark integrated luminosities previously used or recommended
    - LHC: 140 fb^{-1} (Run 2), 200 fb^{-1} (Run 3)
    - HL-HC: 3 ab^{-1}
    - FCC-hh: 2.5, 30 ab^{-1}
- Sensitivity to excited quarks (q*) at pp colliders scales as expected
  - Increases linearly with $\sqrt{s}$ and logarithmically with $\int \mathcal{L}\, dt$.
  - For HL-LHC (14 TeV, 3 ab^{-1}), q* limit at 8 TeV, discovery at 7 TeV
  - For HE-LHC (27 TeV, 10 ab^{-1}), q* limit at 15 TeV, discovery at 13 TeV
  - For FCC-hh (100 TeV, 30 ab^{-1}), q* limit at 50 TeV, discovery at 44 TeV







Summary for generic Z’, CI & other resonances

European Strategy Update Briefing Book

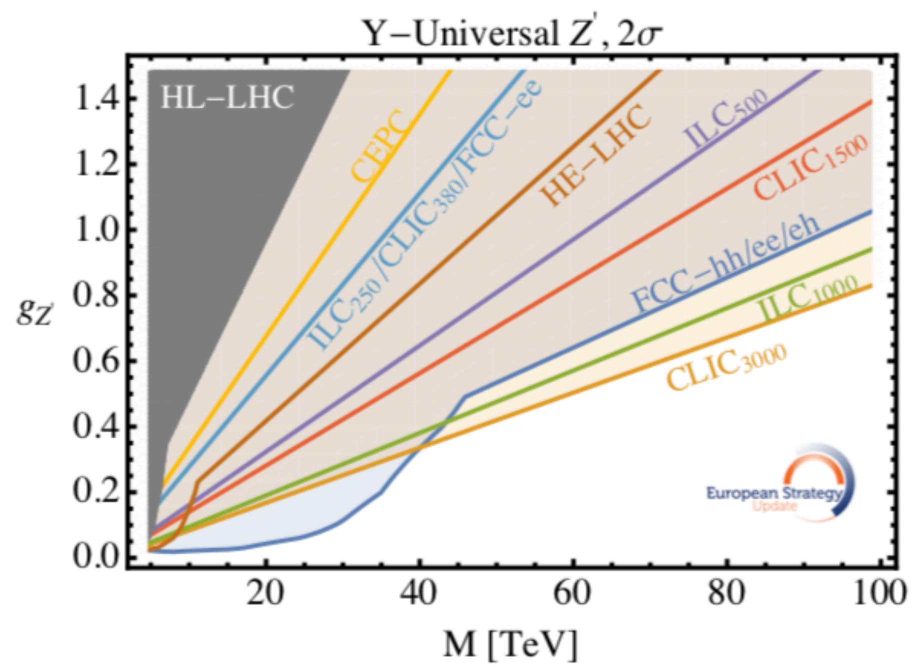


Fig. 8.3: Exclusion reach of different colliders on the Y-Universal Z' model

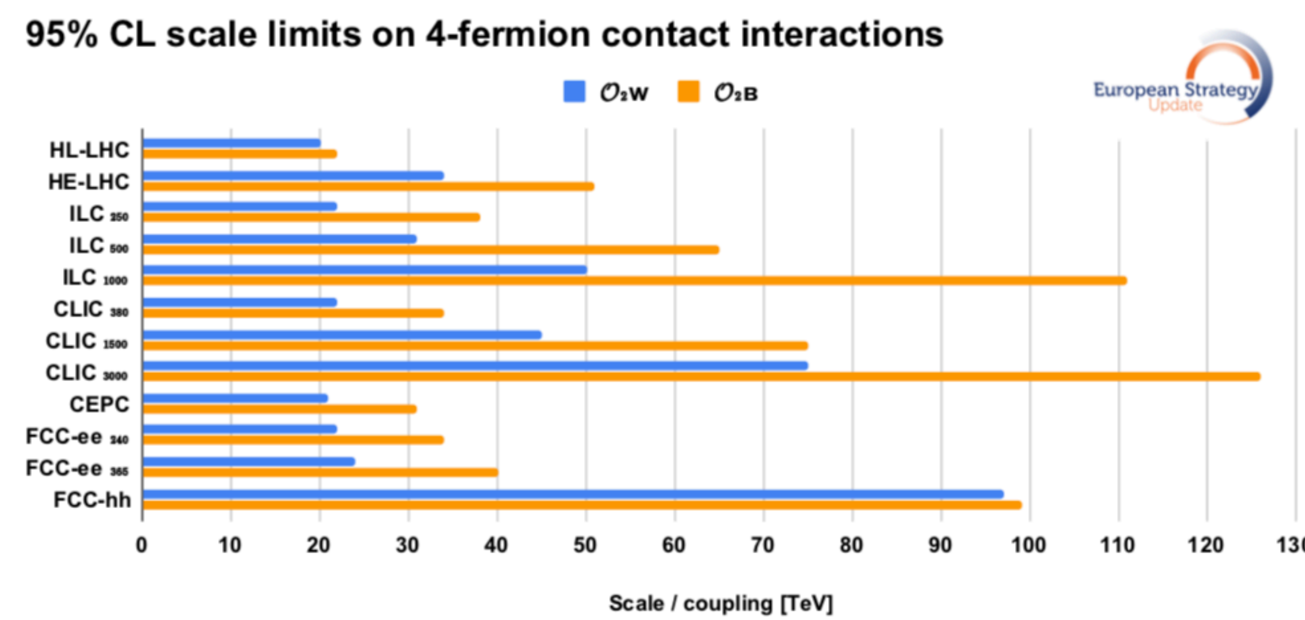


Fig. 8.1: Exclusion reach of different colliders on four-fermion contact interactions from the operators $\mathcal{O}_{2W}$ and $\mathcal{O}_{2B}$. The blue bars give the reach on the effective scale $\Lambda/(g_2^2\sqrt{c_{2W}})$ and the orange bars on $\Lambda/(g_1^2\sqrt{c_{2B}})$, where $c_{2W,2B}$ are the Wilson coefficients of the corresponding operators and the gauge couplings come from the use of the equations of motion.

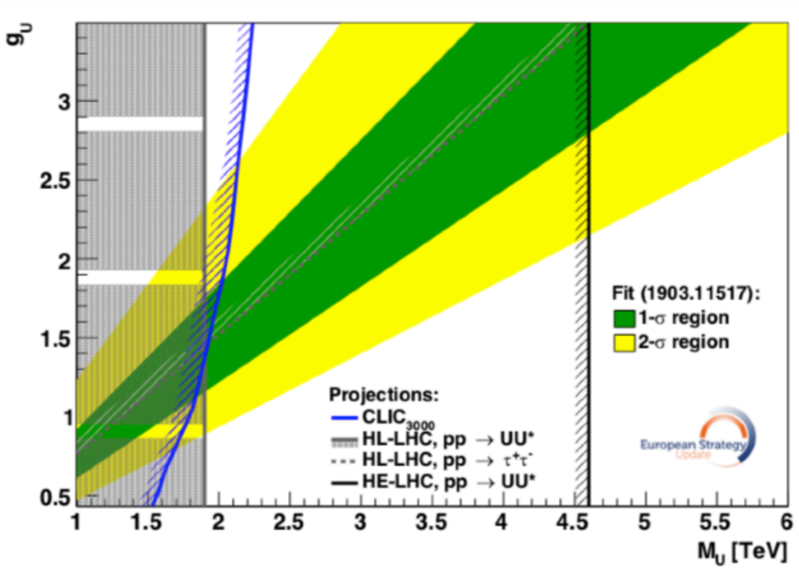


Fig. 8.13: Direct and indirect sensitivity at 95% CL for the vector leptoquark U_1 in the mass versus coupling plane.

Machine-learning-powered searches: a change in mindset?

Maurizio Pierini's talk at IWAPP 2021

Re-embracing the scientific method

- *Research under the scientific method starts gathering information about nature*
- *Instead, our baseline is the SM, which was formed once these informations were gathered*
- *We are victim of our success:*
  - *Since 1970s, we start always from the same point*
  - *We have lost the value of learning from data*
  - *Not by chance, we totally endorsed blind analysis as the ONLY way to search*

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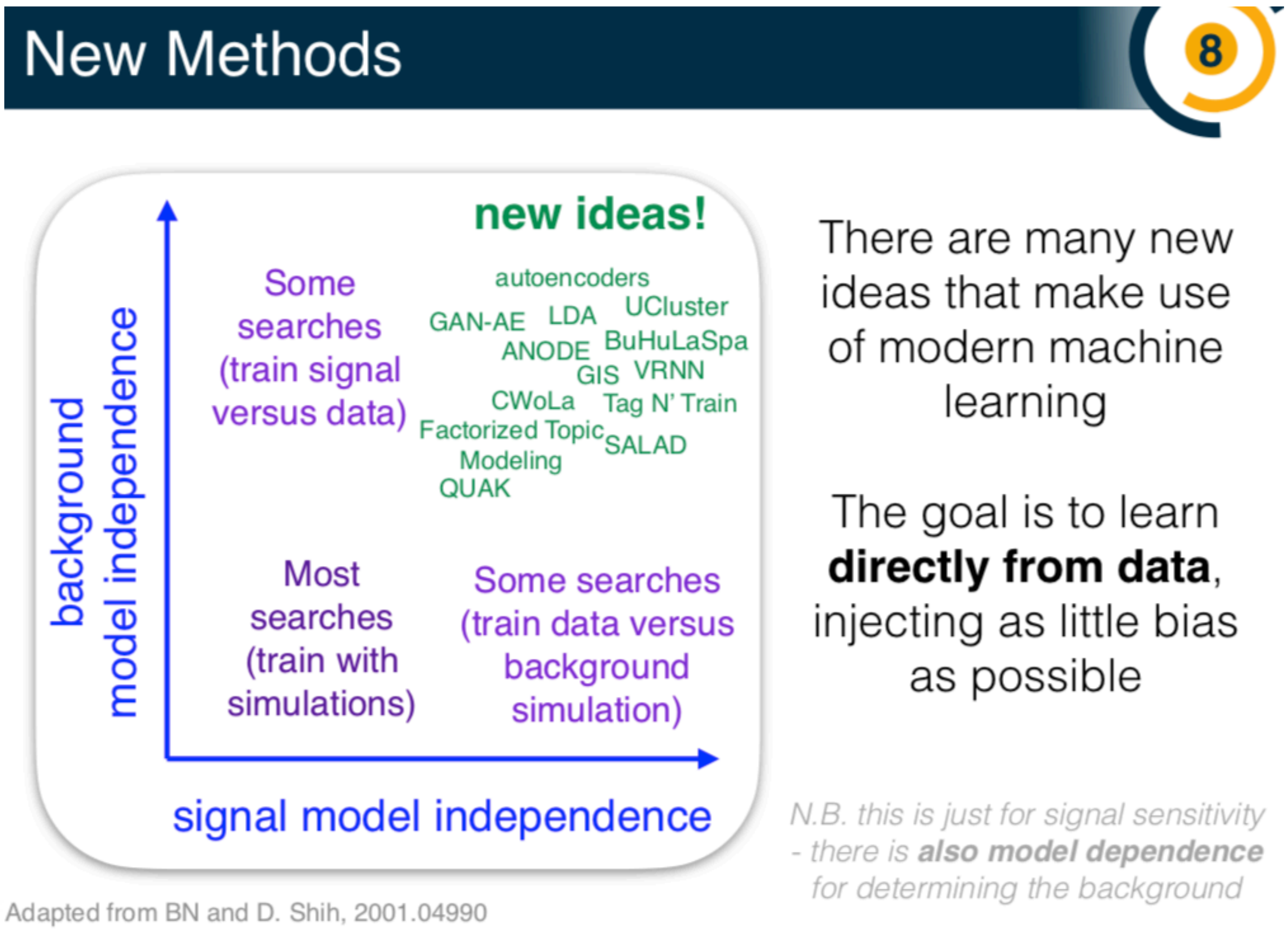
A (not-so-remote) possibility: outlier detection

Ask Me!

A test in controlled conditions: LHC Olympics

Ben Nachman's talk at the 2021 Reinterpretation Workshop



Something similar also happening for Dark Matter in *DarkMachines*

Ask Me!

Related: the importance of *re-using* LHC data

Let's not limit DM collider searches / measurement to one-use-only…

Reinterpret & recast

ATL-PHYS-PUB-2019-032

ATLAS PUB Note
ATL-PHYS-PUB-2019-032
11th August 2019

RECAST framework reinterpretation of an ATLAS Dark Matter Search constraining a model of a dark Higgs boson decaying to two b-quarks

CMS-NOTE-2017-001] ATL-PHYS-PUB-2019-029

Available on the CMS information server CMS NOTE-2017/001

The Compact Muon Solenoid Experiment
CMS Note
Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

2017/11/07

Simplified likelihood for the re-interpretation of public CMS results

The CMS Collaboration

Fit&combine

$$\mathcal{L} = \mathcal{L}_{\text{collider}}\mathcal{L}_{\text{DM}}\mathcal{L}_{\text{flavor}}\mathcal{L}_{\text{EWPO}}\ldots$$

Example: https://gambit.hepforge.org
Eur. Phys. J. C (2019) 79:395

Eur. Phys. J. C (2019) 79:395
https://doi.org/10.1140/epjc/s10052-019-6837-x
THE EUROPEAN PHYSICAL JOURNAL C
Regular Article - Experimental Physics

Combined collider constraints on neutralinos and charginos

GAMBIT Collaboration: Peter Athron[1,2], Csaba Balázs[1,2], Andy Buckley[3], Jonathan M. Cornell[4], Matthias Danninger[5], Ben Farmer[6], Andrew Fowlie[1,2,7], Tomás E. Gonzalo[8], Julia Harz[9], Paul Jackson[2,10], Rose Kudzman-Blais[5], Anders Kvellestad[6,8,a], Gregory D. Martinez[11], Andreas Petridis[2,10], Are Raklev[8], Christopher Rogan[12], Pat Scott[6], Abhishek Sharma[2,10], Martin White[2,10,b], Yang Zhang[1,2]

Use precision measurements

arXiv:1902.03067 arXiv:1606.05296

JHEP
Published for SISSA by Springer
Received: July 6, 2016
Revised: January 20, 2017
Accepted: February 23, 2017
Published: March 14, 2017

Constraining new physics with collider measurements of Standard Model signatures

Jonathan M. Butterworth,[a] David Grellscheid,[b] Michael Krämer,[c] Björn Sarrazin[c] and David Yallup[a]

Reproducibility and reinterpretation
of measurements & searches are important for:
1. the scientific method
2. use of our results by others (e.g. theorists)
3. the future of the field,
in terms of what to do / prioritize next
→ worth going beyond"measurement/discovery/null result"!

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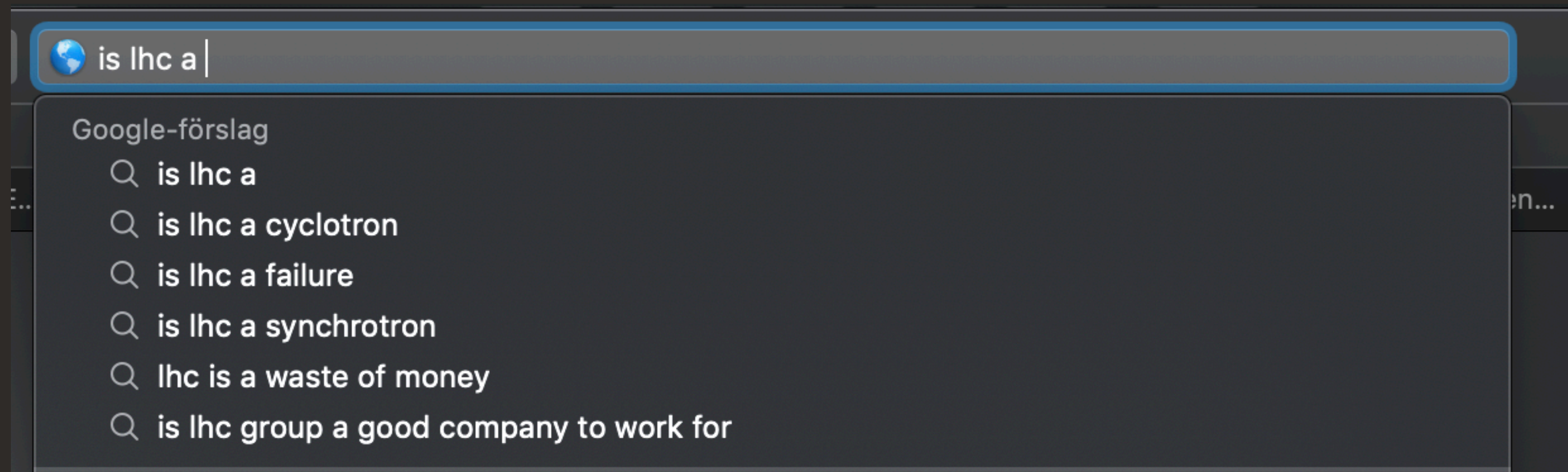
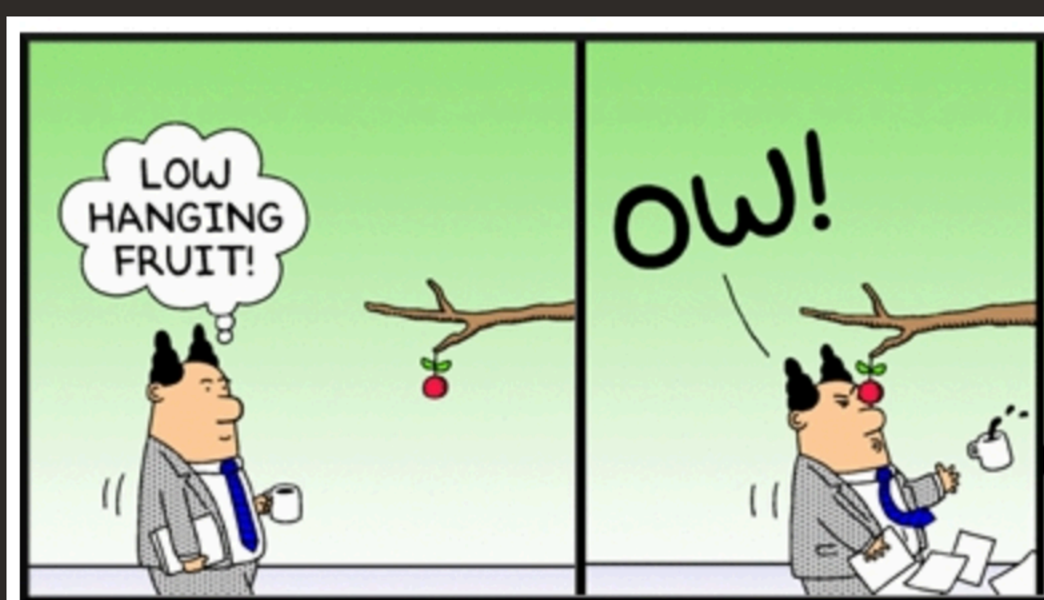
Can we do both, and learn the SM + search for anomalies at the same time? Ask me! & IBM next year…

What to do in absence of excesses?



My feeling about future collider physics:



Dilbert comics

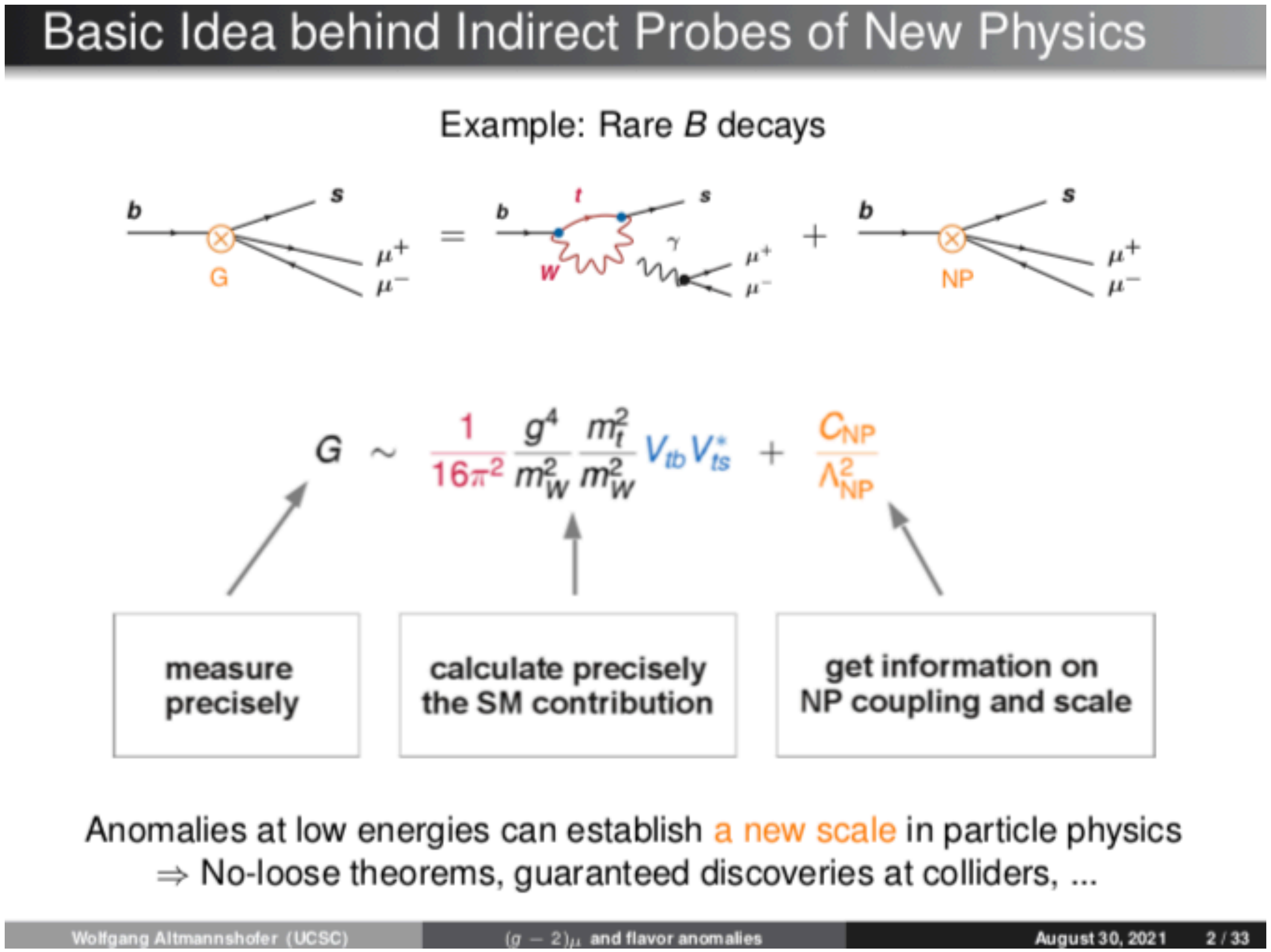
Let's keep looking!

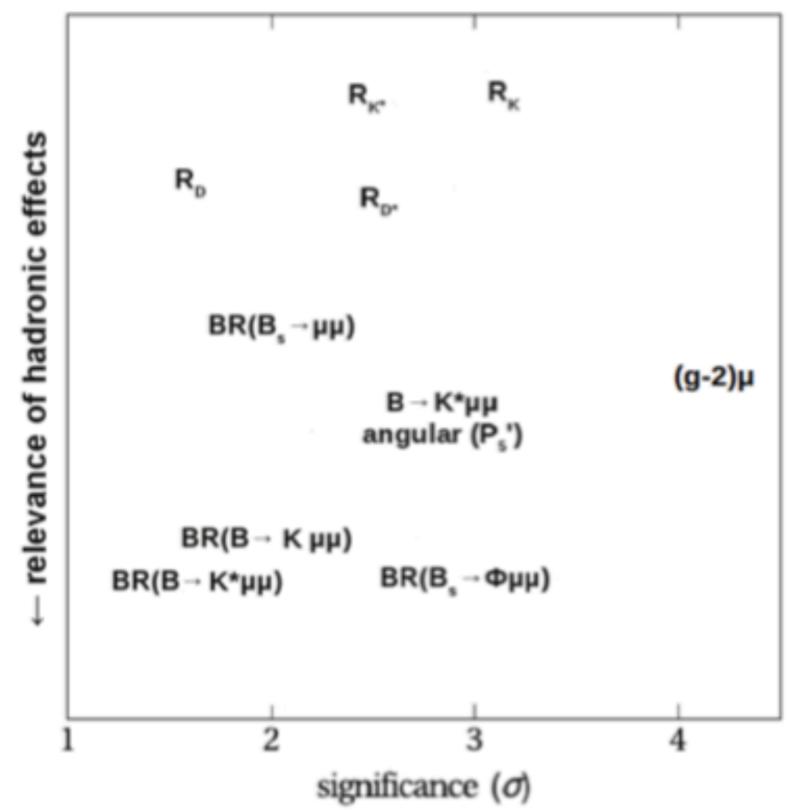
New physics could still manifest in:

1. deviations through precision
2. rare, unusual processes

An inspirational slide

W. Altmannshofer, Talk at Energy Frontier Restart Workshop





(inspired by Zoltan Ligeti)

Outlook (TLDR) on results everyone has been talking about

$(g-2)_\mu$

- $\Lambda_{NP} \lesssim 290$ TeV
- best motivated NP scenarios are plausibly in reach of the LHC
- almost guaranteed to see something at a muon collider

R_K, R_{K^*} and friends

- $\Lambda_{NP} \lesssim 120$ TeV
- some scenarios in reach of the LHC; but the generic scale is higher
- would like a 100 TeV collider and/or a muon collider to systematically explore NP models

R_D, R_{D^*}

- $\Lambda_{NP} \lesssim 8$ TeV
- should have already seen something at the LHC
- new physics should be around the corner

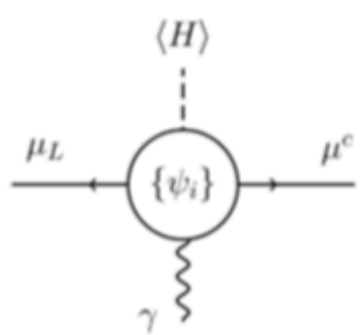
Probing $(g-2)_\mu$ at a Muon Collider

- In the strongly coupled case, the new physics scale might be too high to be probed directly anytime soon. But there is a model independent signature at a muon collider, Buttazzo, Paradisi 2012.02769

$$\sigma(\mu\mu \to h\gamma) \simeq 0.7\text{ab} \times \left(\frac{\sqrt{s}}{30\text{ TeV}}\right)^2 \left(\frac{\Delta a_\mu}{3 \times 10^9}\right)^2$$

- Weakly coupled simplified models are essentially guaranteed to be discovered at a muon collider.

See the exhaustive survey of all particles that can show up in the loop by Capdevilla et al. 2006.16277, 2101.10334

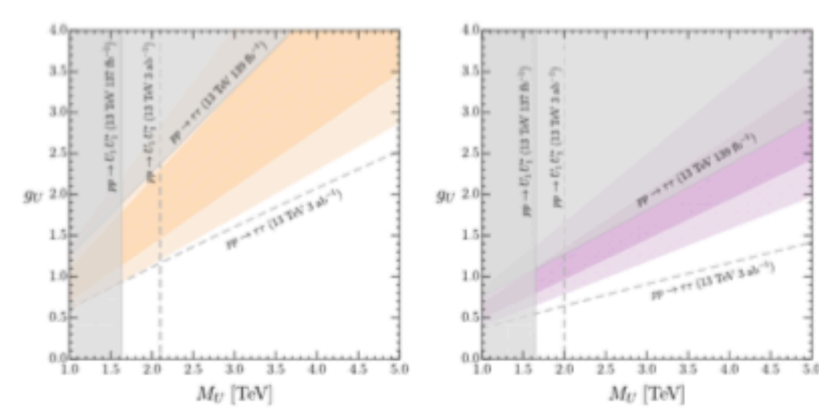


W. Altmannshofer, Talk at Energy Frontier Restart Workshop

Wolfgang Altmannshofer (UCSC) $(g-2)_\mu$ and flavor anomalies August 30, 2021

Simplified Models for $R_{D^{(*)}}$ at the LHC

- W' models excluded by direct searches
- Charged Higgs bosons strongly constrained by $B_c \to \tau\nu$ and $B \to D^{(*)}\tau\nu$ kinematic distributions
- "3rd gen." leptoquarks can work. At colliders, look for pair production, single production, or modifications to $pp \to \tau\tau$



Cornella et al. 2103.16558

Preferred leptoquark parameter space can be covered at the high-luminosity LHC

Wolfgang Altmannshofer (UCSC) $(g-2)_\mu$ and flavor anomalies August 30, 2021 31 / 33

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SM problems we may actually have

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Should we believe in aesthetics?

Aesthetical problems with the SM

Empirical problems with the SM

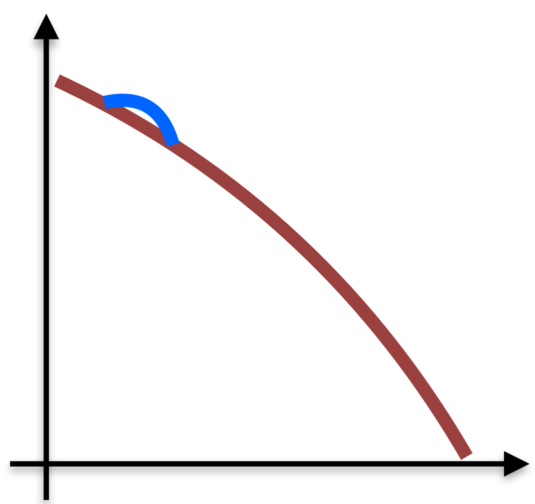
- Dark matter (DM)
- Dark energy
- Matter vs antimatter
- Weakness of gravity
- Neutrino masses

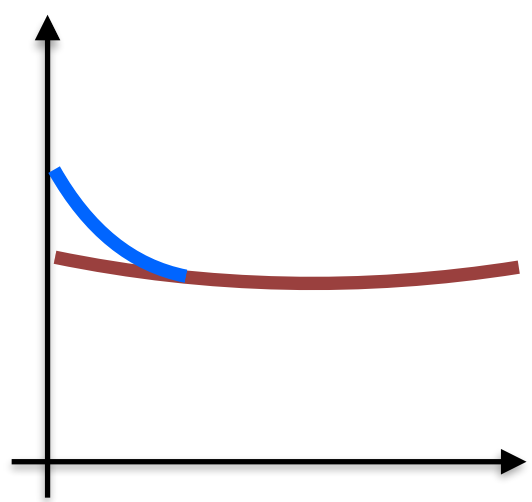
Prioritisation is not for experimentalists…but in Raman Sundrum's words

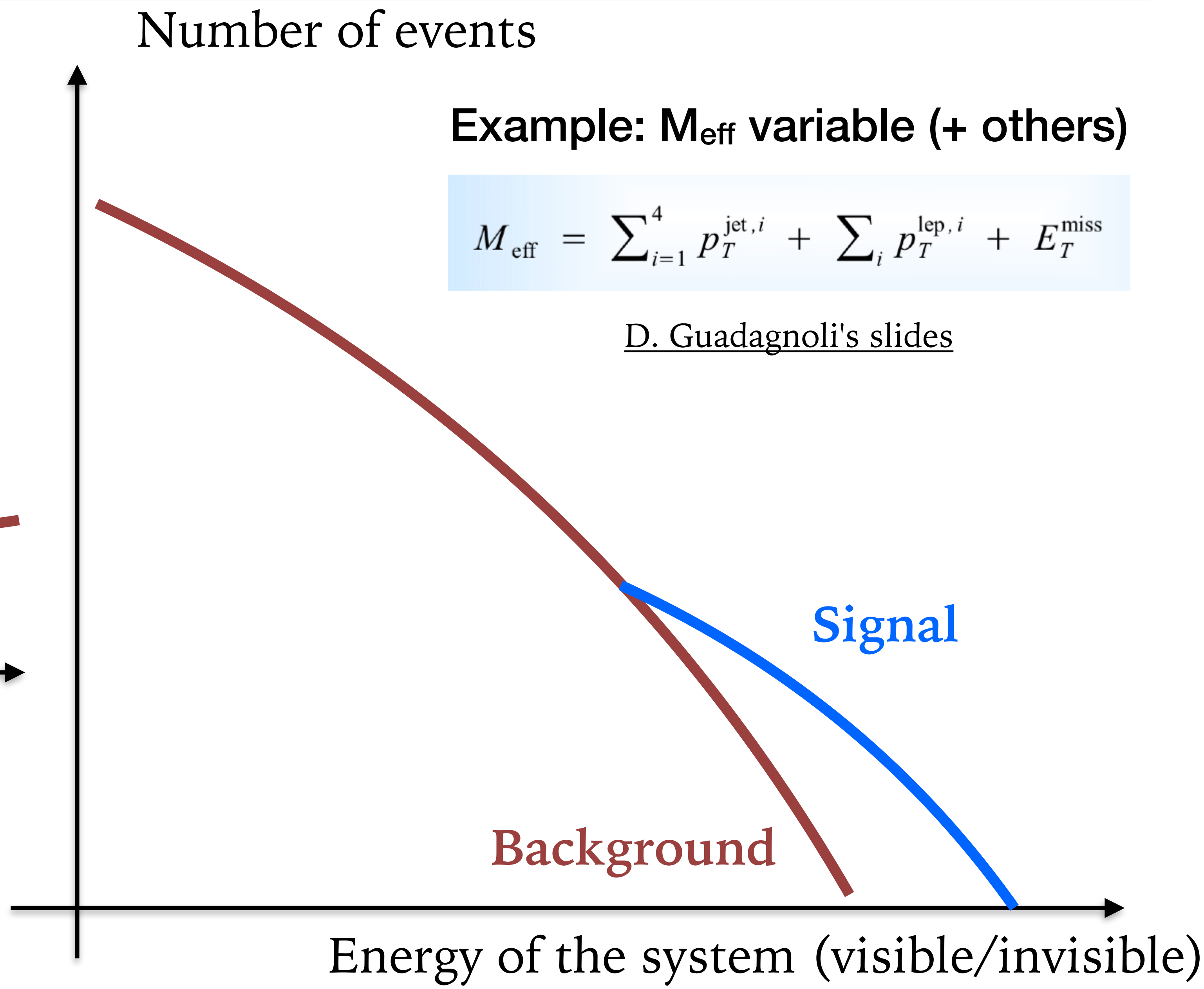
> *What you think is plausible plays a big role in making superhuman (not just human) efforts to make discoveries, as that is what it might take. So I think there's nothing wrong with saying dark matter is a big mystery, and even that mystery may be informed by considerations of naturalness.*

What collider enthusiasts like: many answers can lie in the **TeV-scale**

(some highlights of) SUSY at future colliders







Example: M_{eff} variable (+ others)

$$M_{\text{eff}} = \sum_{i=1}^{4} p_T^{\text{jet},i} + \sum_i p_T^{\text{lep},i} + E_T^{\text{miss}}$$

D. Guadagnoli's slides

- Higher collider energy (pp) → *more* MET
- Cleaner environment (ee) → *better* MET

Opportunities and challenges for hadron colliders

- Generally best reach to discovery of high-mass states [V. Shiltsev's talk]
- Challenges: online data taking thresholds, simultaneous collisions (pile-up)

arXiv:1902.10229 and CMS-PAS-FTR-18-016 …more on this later arXiv:1902.10229 and ATL-PHYS-PUB-2018-038

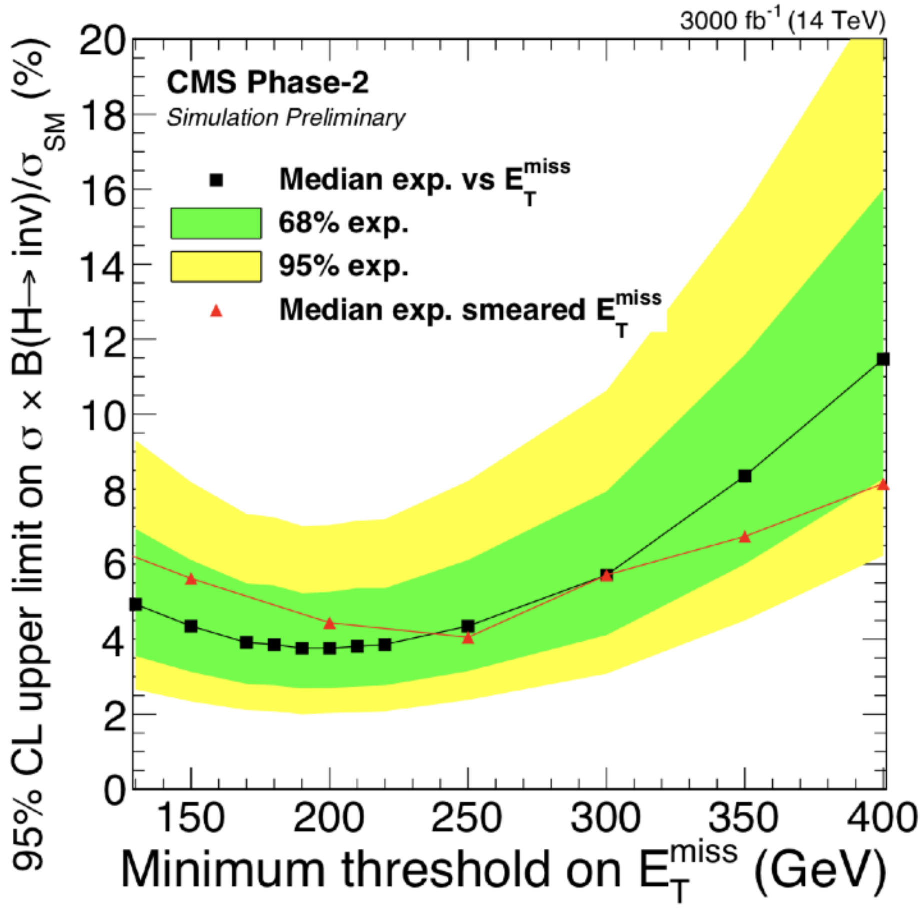
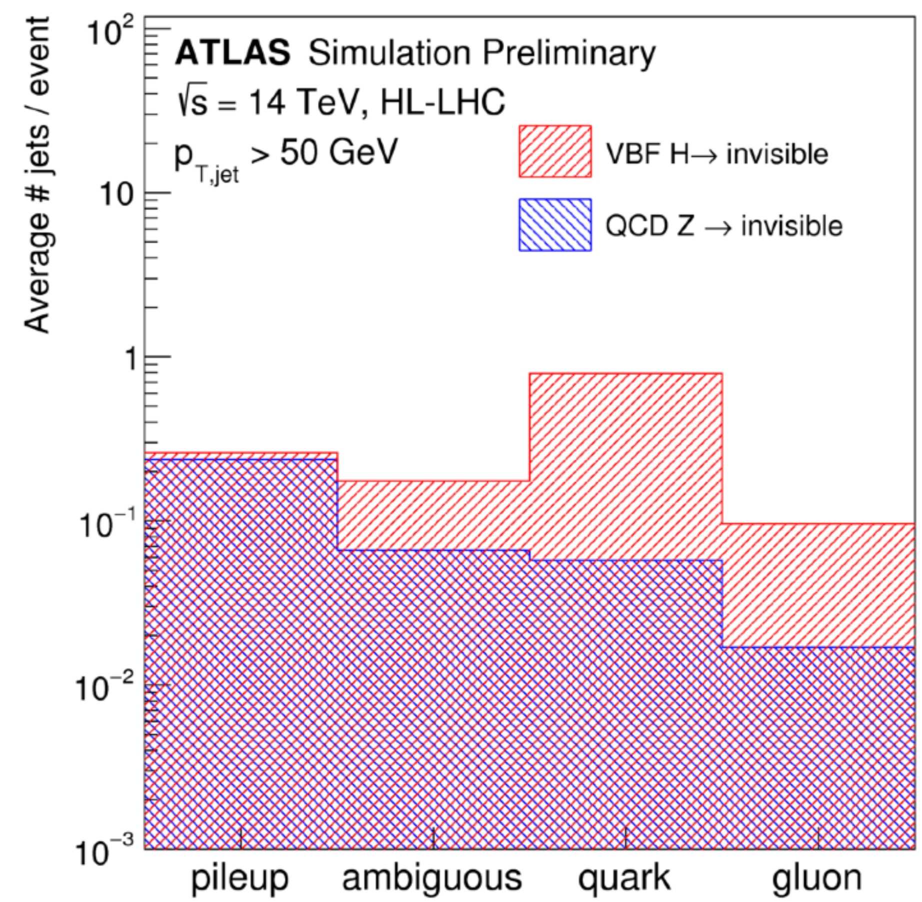


Fig. 113: Left: 95% CL limits on B(H → inv.)
$M_{jj} > 2500$ GeV and an integrated luminosity of 3
with different integrated luminosities.



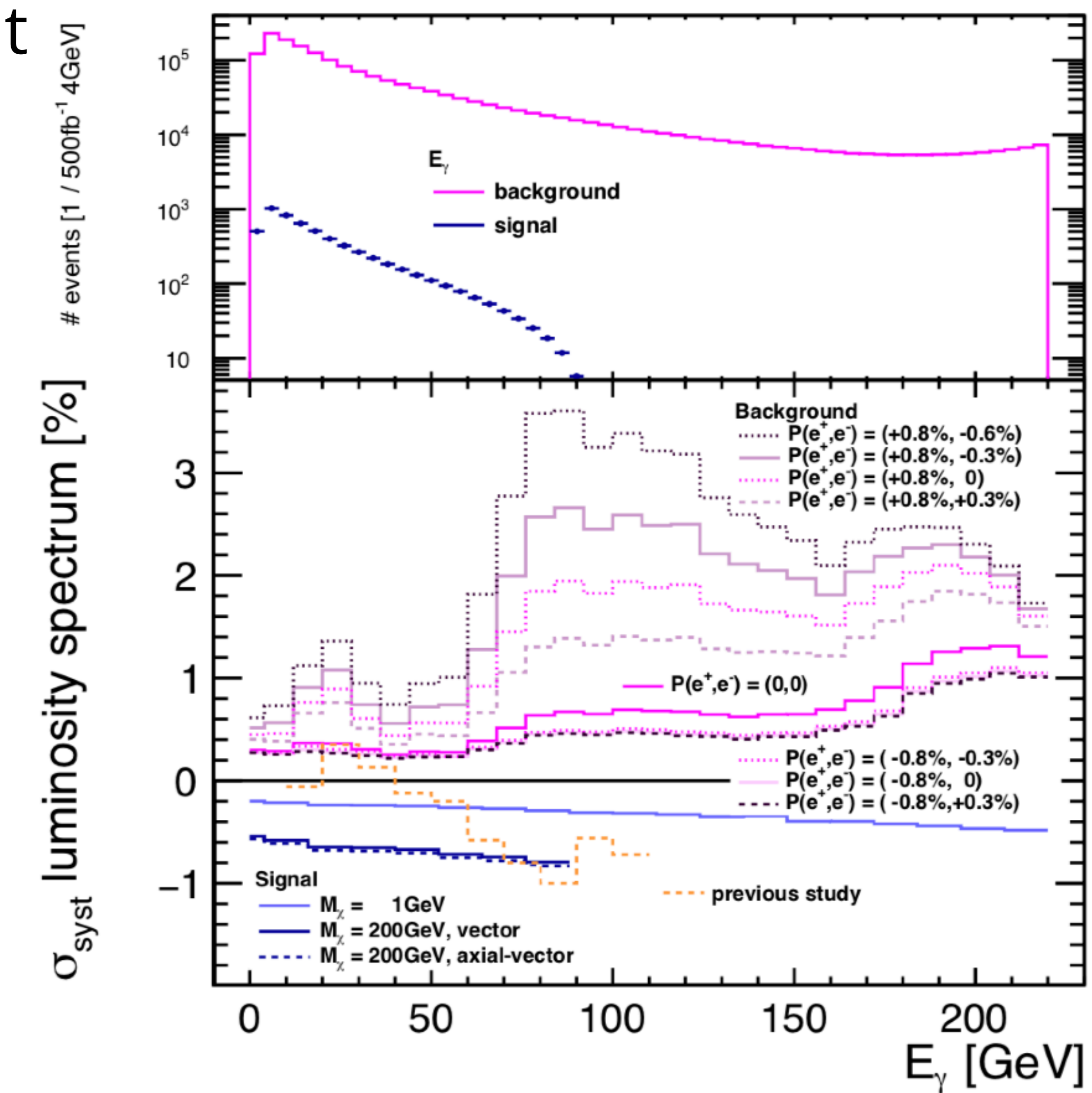
HL-LHC uncertainty on Higgs to invisible BR (VBF) depends on pile-up rejection method

- Main experimental uncertainties: energy scales, simulation modelling, luminosity

Opportunities and challenges for e^+e^- colliders

Muon collider is a slightly different beast, see later

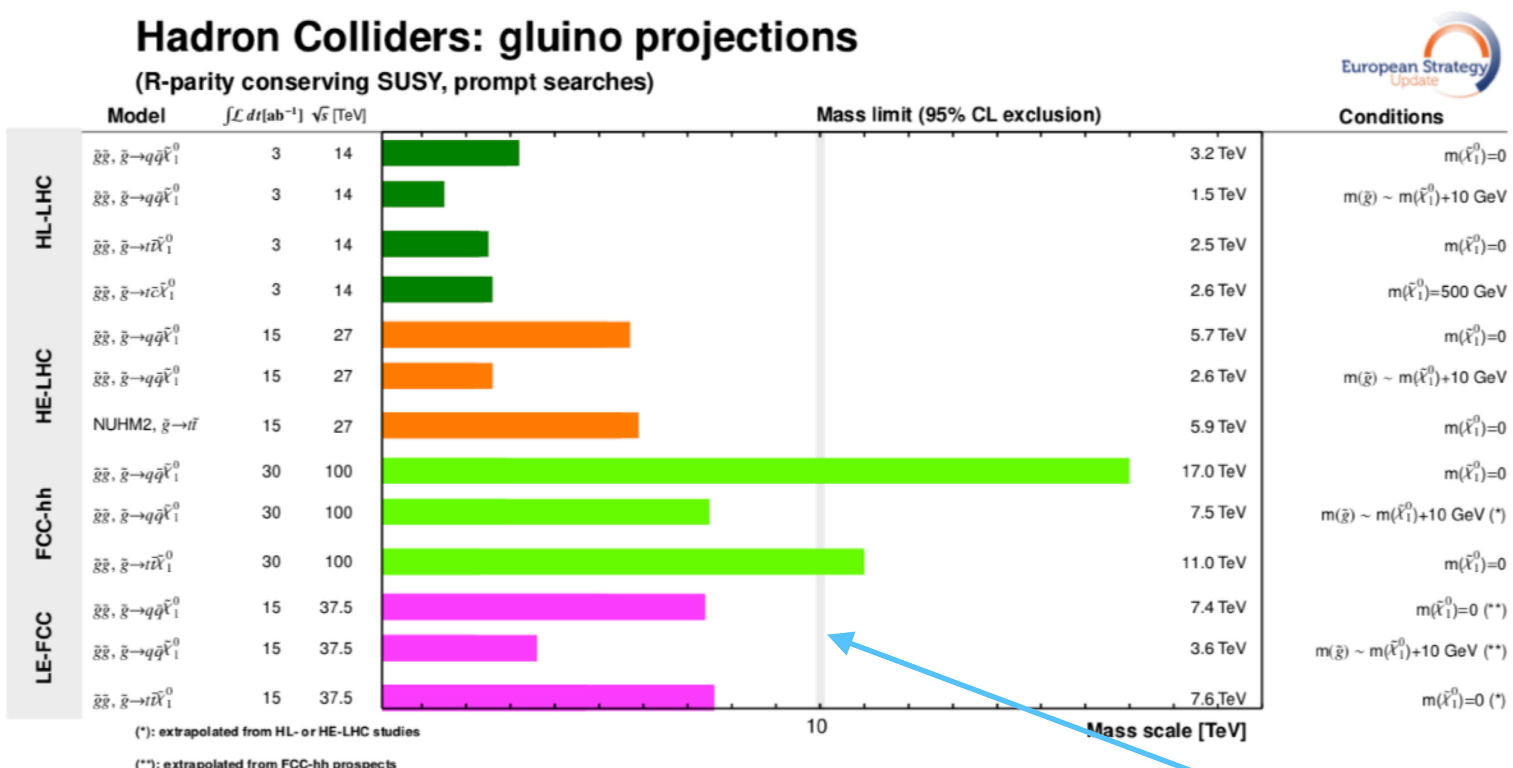
- Limited by CoM energy but clean environment
  - still reasonable reach in new energy scales
- Lower backgrounds
  - Can probe lower masses, and/or search for other theory benchmarks at a later stage
- Specific strengths of lepton colliders:
  - clear tagging (e.g. for Higgs recoiling against Z, invisible particle recoiling against visible ones)
  - beam polarization can enhance/help identify signal
- Main experimental uncertainties: luminosity, electron identification (theory also similar magnitude)

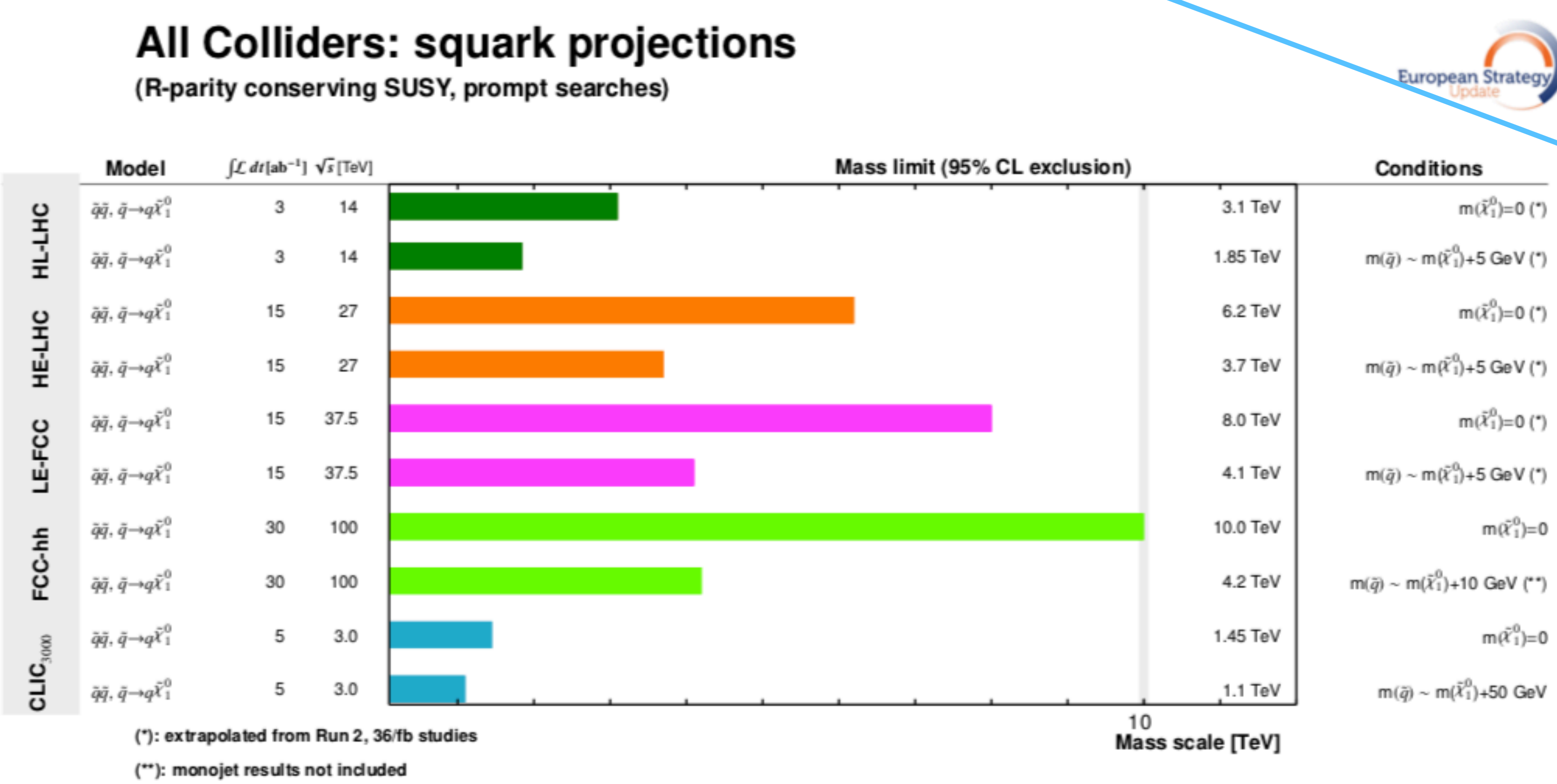


M. Habermehl's PhD thesis

Some SUSY prospects at future colliders

European Strategy Update Briefing Book





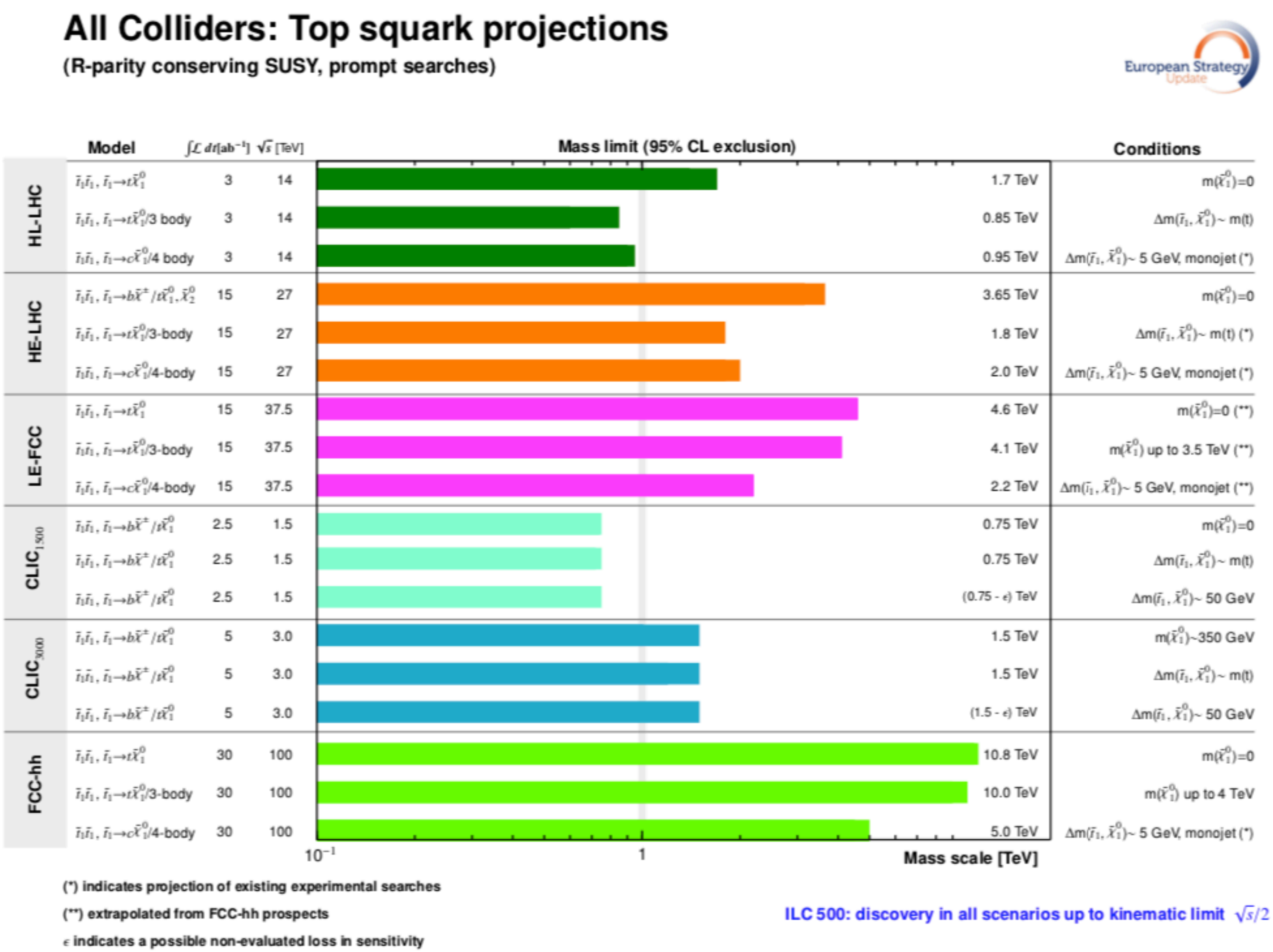
Fine tuning parameter (details in backup):

ε	High-scale mediation	Low-scale mediation
stop	$5\times 10^{-5}\left(\frac{10\ \text{TeV}}{m_{\tilde{t}}}\right)^2$	$2\times 10^{-3}\left(\frac{10\ \text{TeV}}{m_{\tilde{t}}}\right)^2$
gluino	$7\times 10^{-6}\left(\frac{17\ \text{TeV}}{m_{\tilde{g}}}\right)^2$	$6\times 10^{-3}\left(\frac{17\ \text{TeV}}{m_{\tilde{g}}}\right)^2$

For discussion:
is this a “moving naturalness target”?

More SUSY prospects at future colliders

European Strategy Update Briefing Book



Note: Electroweak SUSY kept for discussion on dark matter

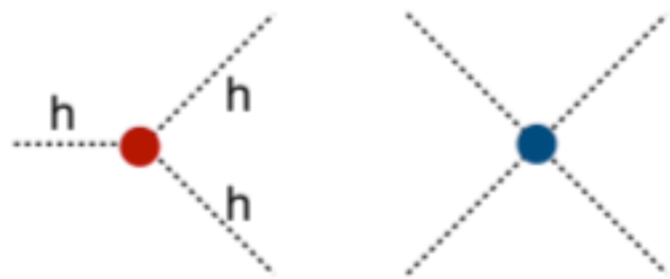
Higgs BSM (in very broad strokes): self-couplings

Higgs Potential is given by:

$$V(\phi^*\phi) = \mu^2(\phi^*\phi) + \lambda(\phi^*\phi)^2$$

For fluctuations about the minima, $\phi \rightarrow v + h$

$$V = V_0 + \frac{m_h^2}{2}h^2 + \underbrace{\frac{m_h^2}{2v^2}}_{\lambda_{HHH}^{SM}}vh^3 + \underbrace{\frac{m_h^2}{8v^2}}_{\lambda_{HHHH}^{SM}}h^4$$



Results in di-Higgs production!

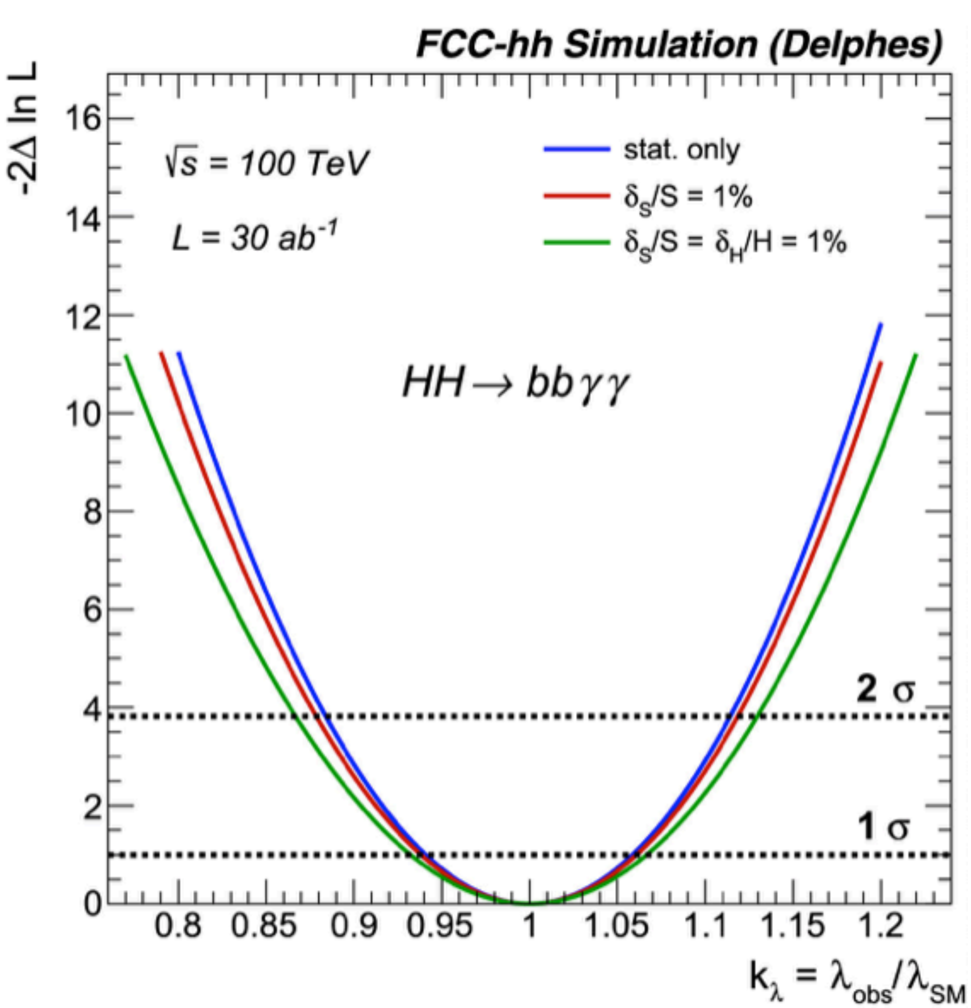
Measuring all the Higgs **self-couplings** will confirm the SM nature of the Higgs boson

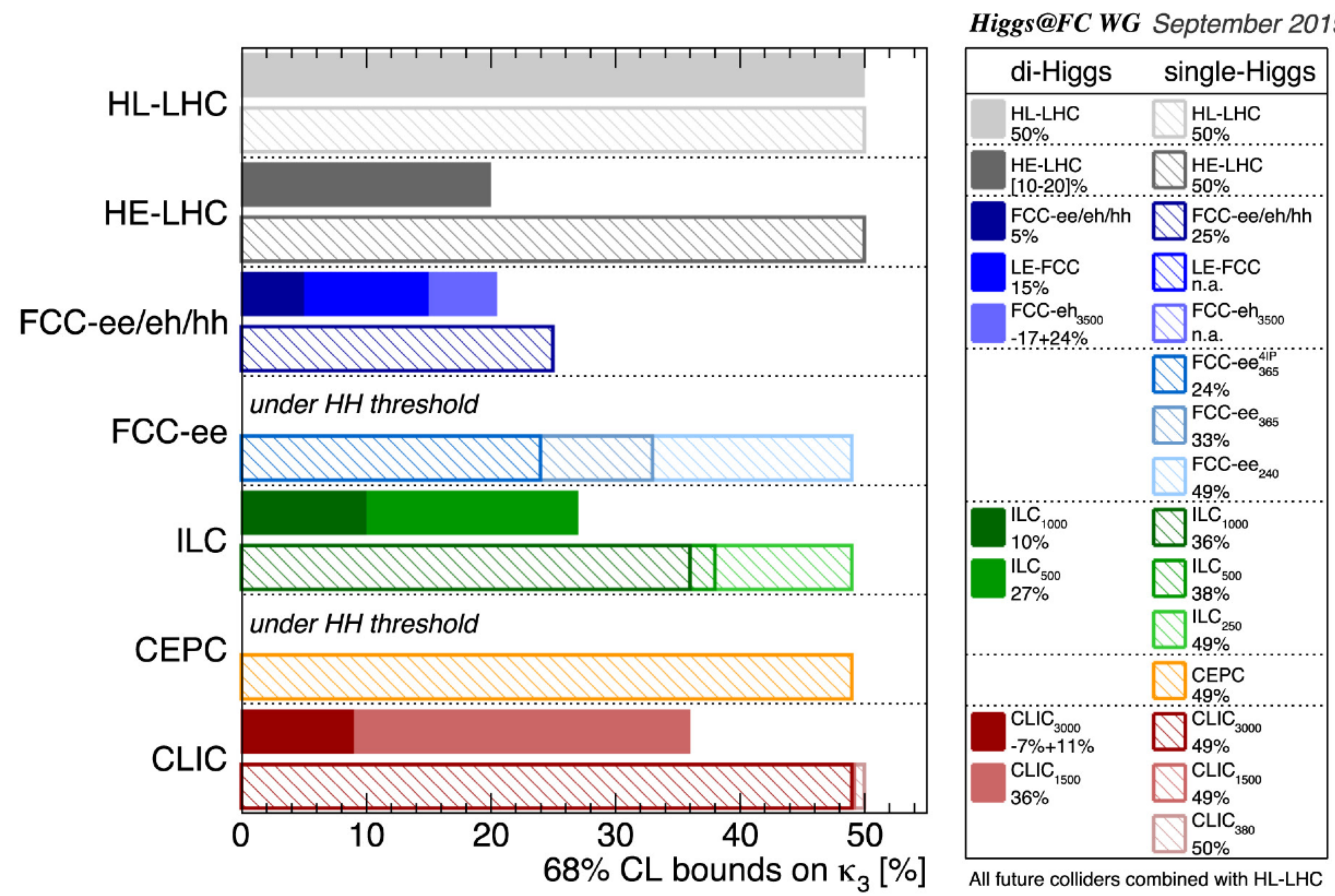
Observing **enhancements** of di-Higgs production means e.g. that there are other new particles decaying into HH or new loop processes

Higgs self-couplings at future colliders

Sensitivity (~bounds, in %) of the SM value of the Higgs self-coupling (H→HH)

Example of precision for a single channel





(a)

European Strategy Update Briefing Book and FCC physics prospects

H. Gray, Reviews in Physics 6 (2021) 100053

European Strategy Update Briefing Book

More Higgs BSM (in very broad strokes): Higgs-like states, compositeness

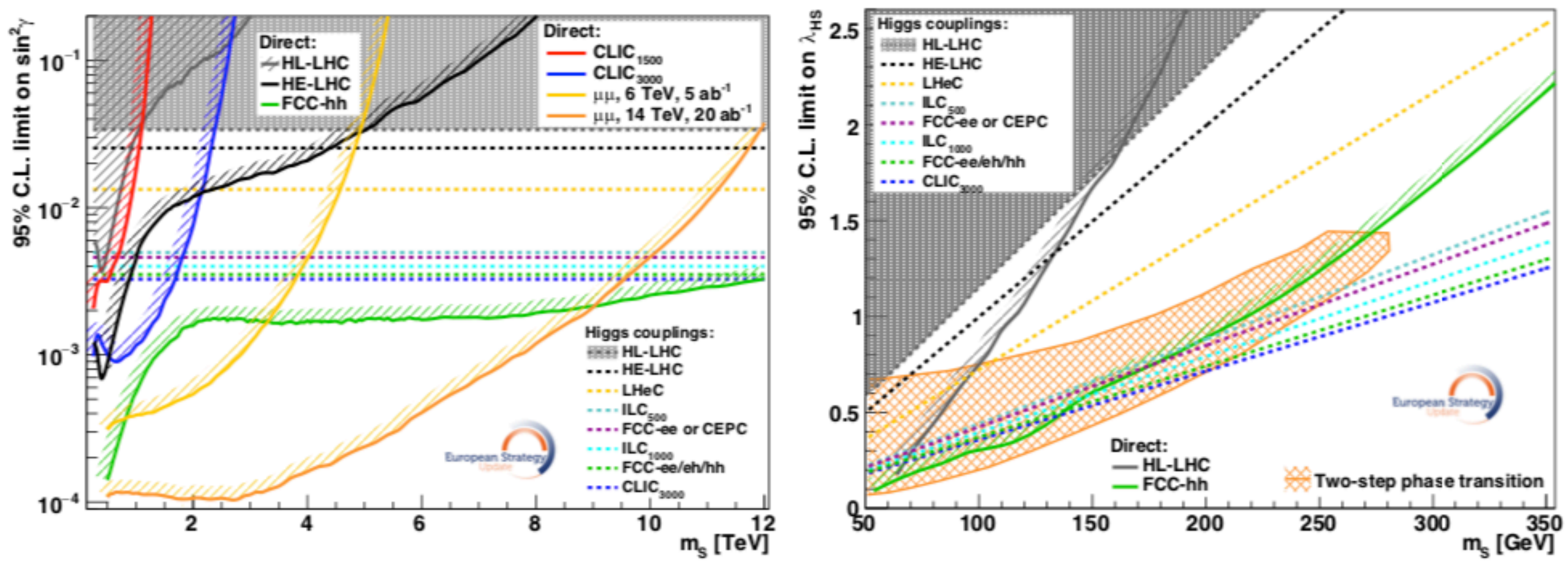


Fig. 8.11: Direct and indirect sensitivity at 95% CL to a heavy scalar singlet mixing with the SM Higgs boson (left) and in the no-mixing limit (right). The hatched region shows the parameters compatible with a strong first-order EW phase transition.

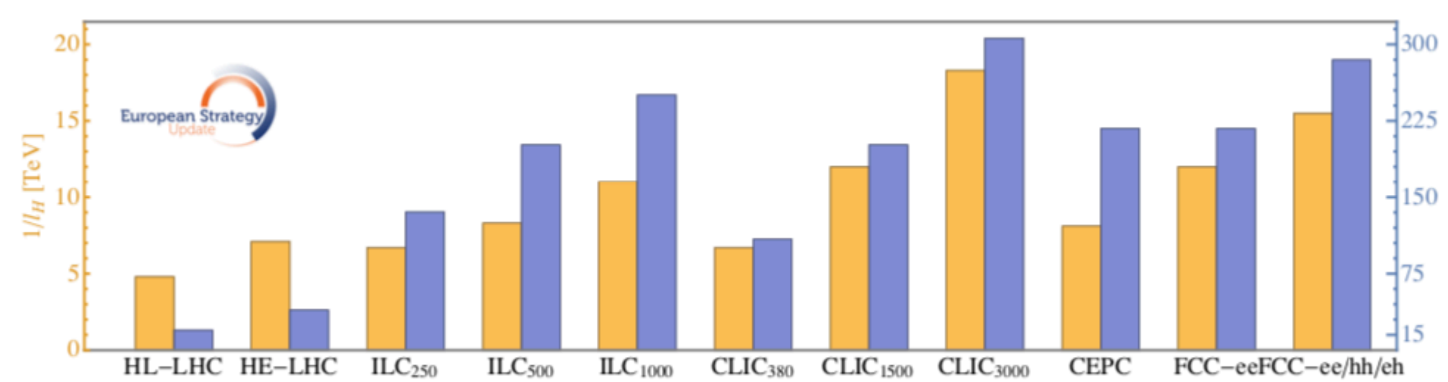
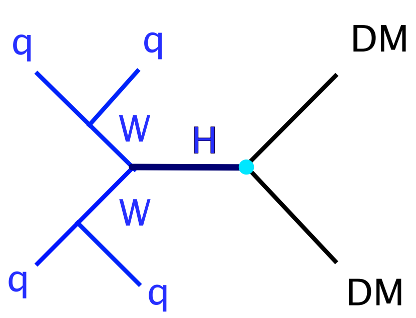
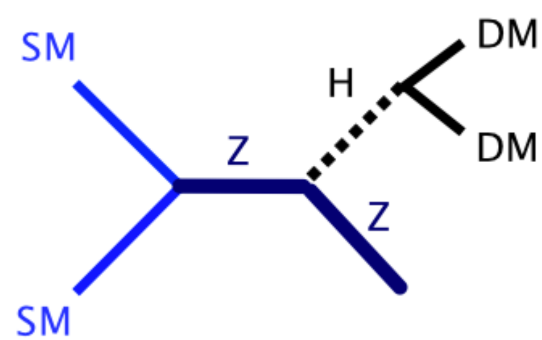


Fig. 8.5: Exclusion reach of different colliders on the inverse Higgs length $1/\ell_H = m_*$ (orange bars, left axis) and the tuning parameter $1/\varepsilon$ (blue bars, right axis), obtained by choosing the weakest bound valid for any value of the coupling constant g_*.

Higgs portal (dark matter? see later)

Higgs to invisible constraints
interpreted as **Higgs Portal** models



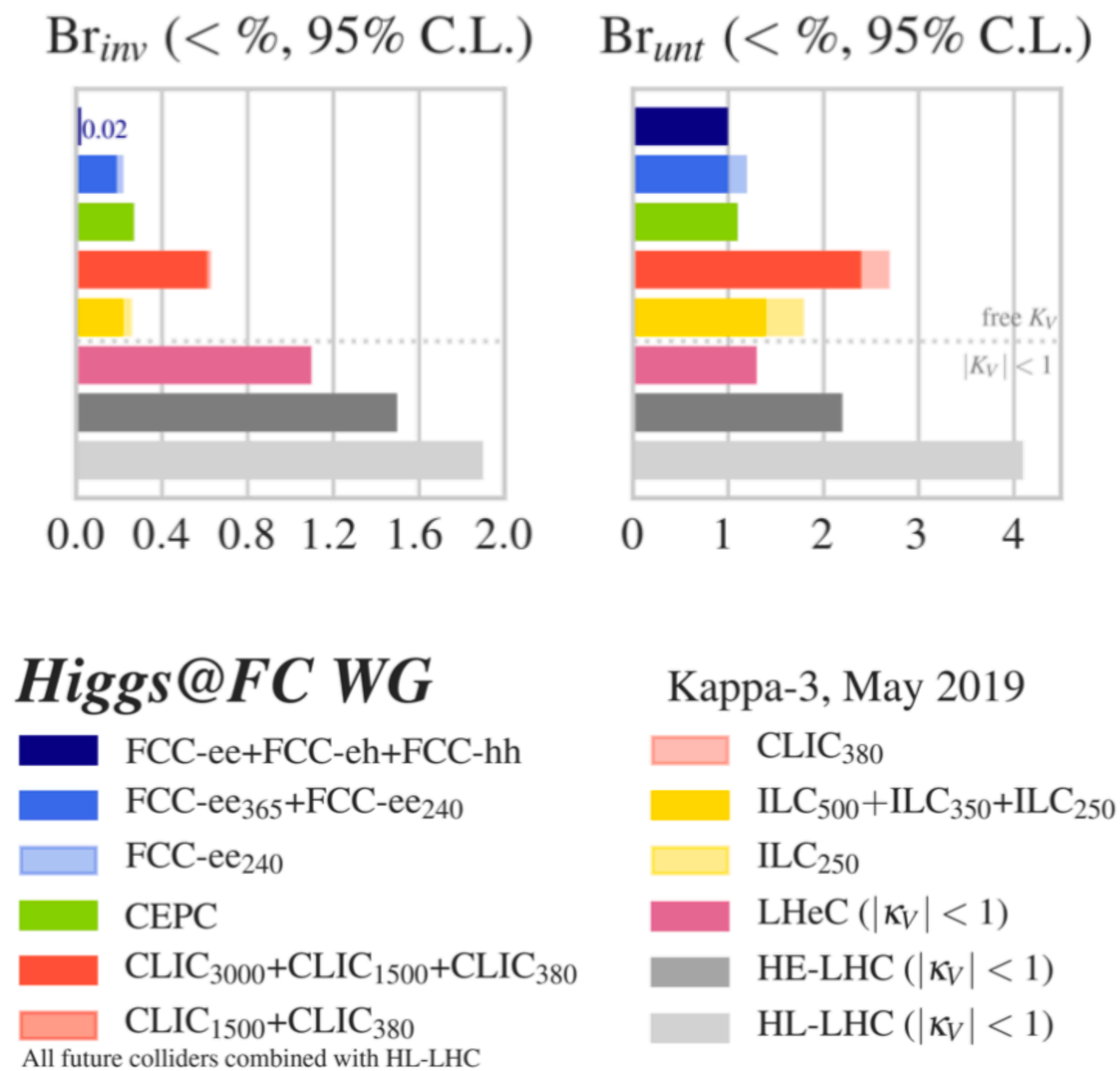


arXiv:1905.03764 used for plots used for plots

Collider	95% CL upper bound on BR_{inv} [%]		
	Direct searches	kappa-3 fit	Fit to BR_{inv} only
HL-LHC	2.6	1.9	1.9
HL-LHC & HE-LHC		1.5	1.5
FCC-hh	0.025	0.024	0.024
HL-LHC & LHeC	2.3	1.1	1.1
CEPC	0.3	0.27	0.26
$FCC\text{-}ee_{240}$	0.3	0.22	0.22
$FCC\text{-}ee_{365}$		0.19	0.19
ILC_{250}	0.3	0.26	0.25
ILC_{500}		0.22	0.22
$CLIC_{380}$	0.69	0.63	0.60
$CLIC_{1500}$		0.62	0.41
$CLIC_{3000}$		0.61	0.30

LHeC	5.5 (2-sigma, no syst.)
HE-LHeC	3.4 (2-sigma, no syst.)
FCC-eh	1.7 (2-sigma, no syst.)

arXiv:1903.03616



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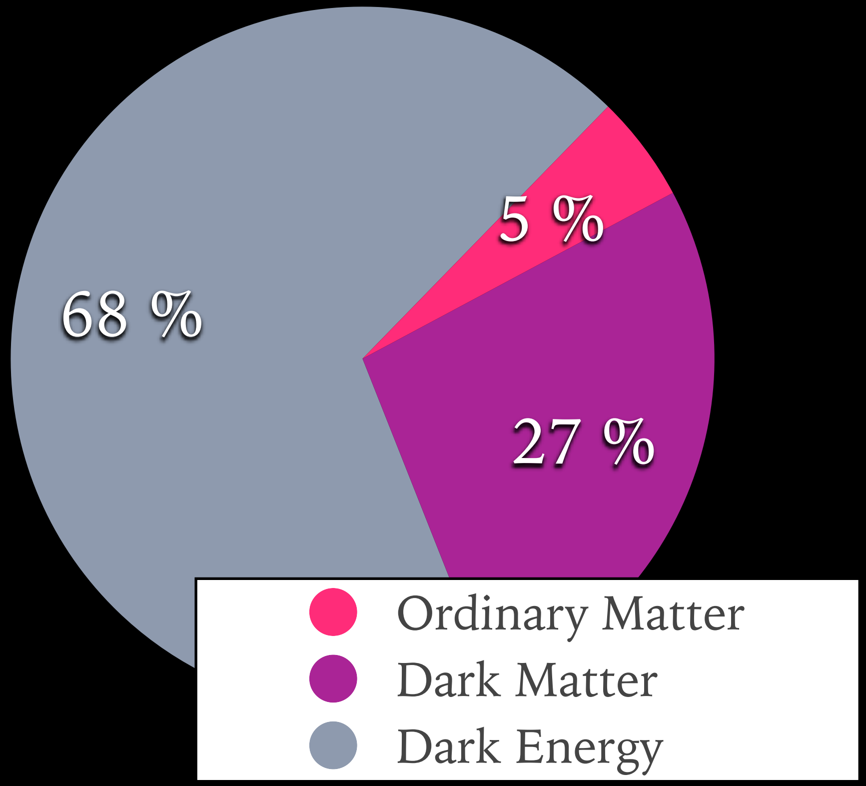
SM problems we definitely have (in particular, dark matter)

European Research Council
Established by the European Commission

You may all have already heard of the WIMP miracle...



Dark Matter constitutes
most of the matter
in the universe

relic density

many caveats and options on how to get it:
see J. Harz's talk on Monday

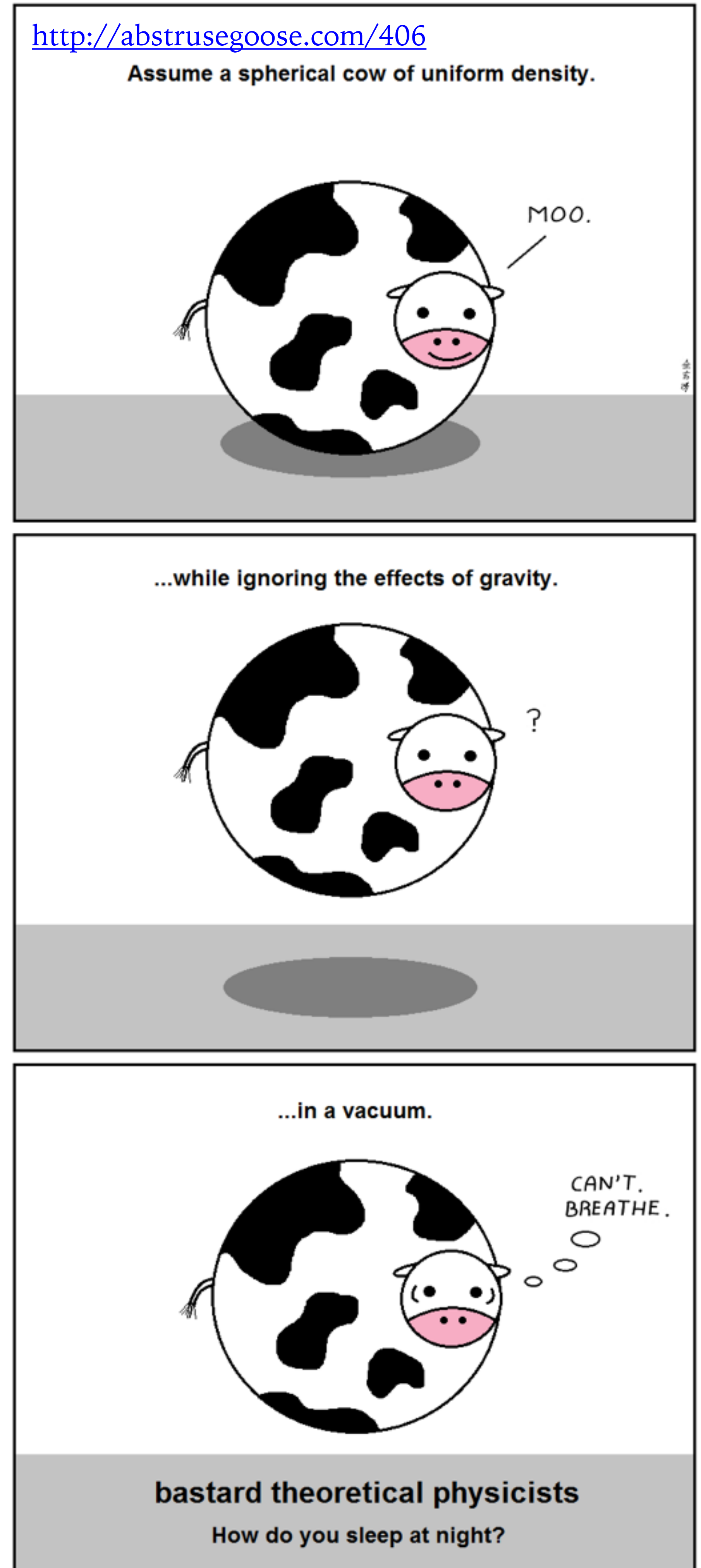
This relic density can be explained with

a new particle

- that interacts only weakly with known matter
- with mass in the range of current experiments

(WIMP)

Under these assumptions…



…we could discover Dark Matter in the next decade!

Unless…

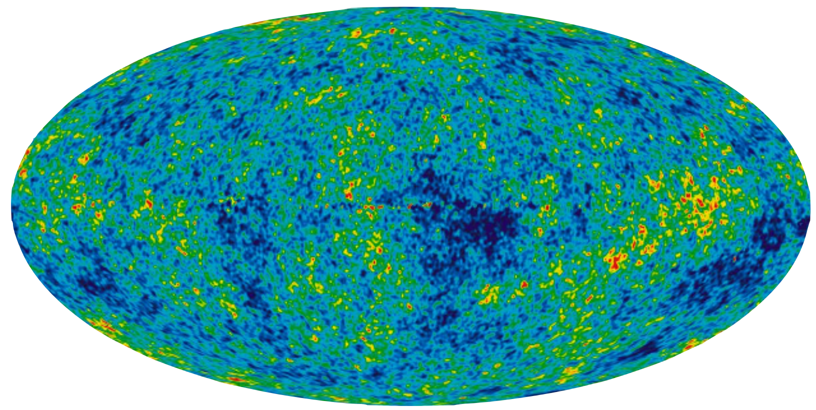
(this is here just to avoid constantly singling out theorists in jokes)

More seriously: the *relic density*

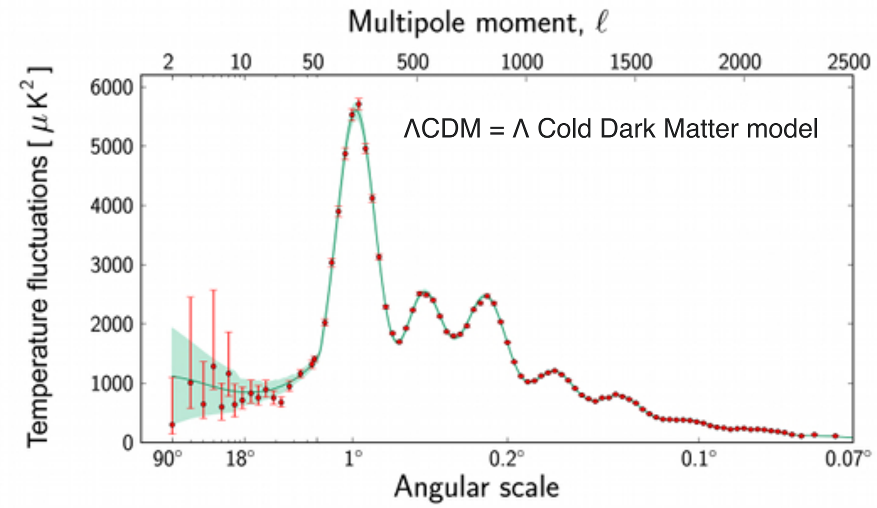
The Nobel Prize in Physics 2019

Ill. Niklas Elmehed. © Nobel Media.
James Peebles
Prize share: 1/2

"for theoretical discoveries in physical cosmology"

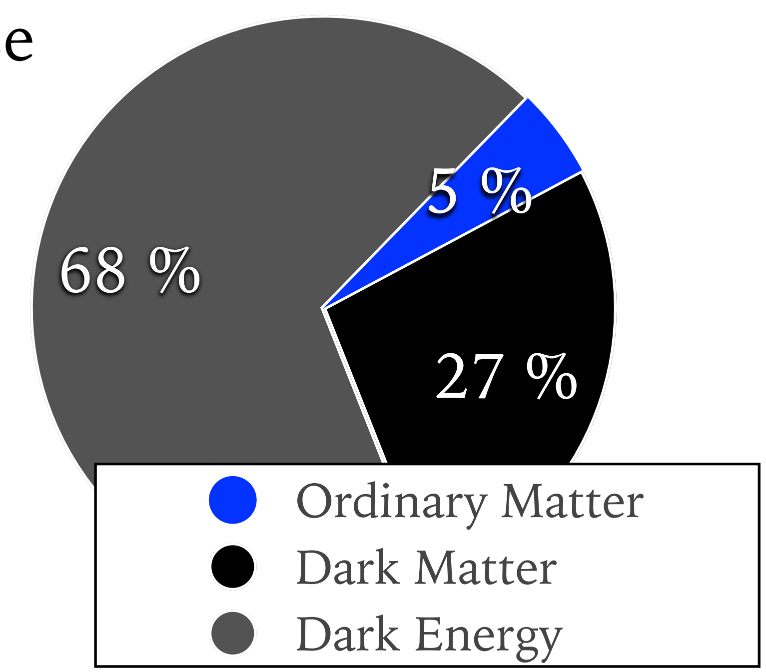


https://sci.esa.int/s/Wnqq4bw



Dark matter constitutes **most of** **the** **matter** in the universe

The DM we measure today **[relic DM density]**
already points at some properties of DM candidates
(e.g. dark, stable)
can it **guide us further**?



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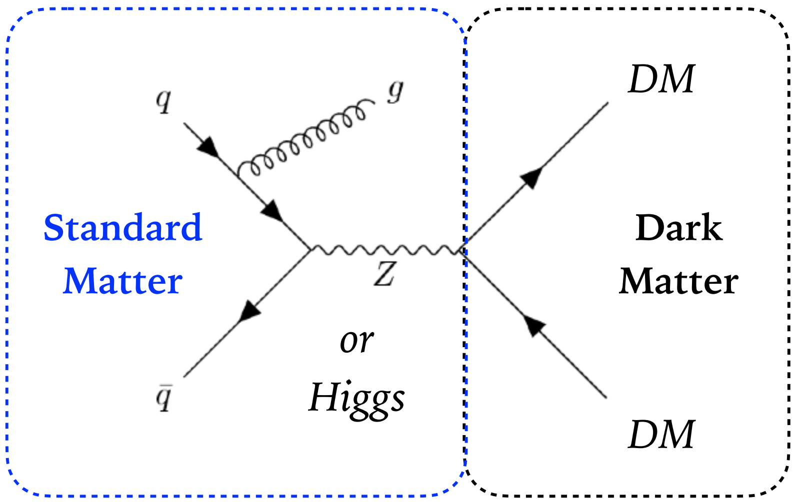
Weakly Interacting Massive Particles

A **minimal** option to make up 100% of the relic density:

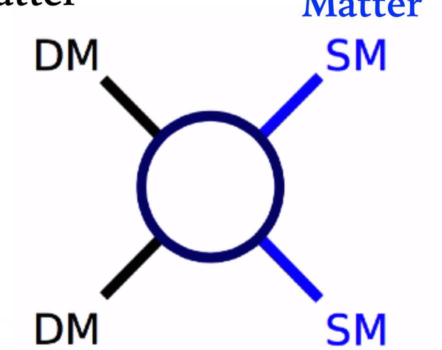
- only add one particle to the Standard Model



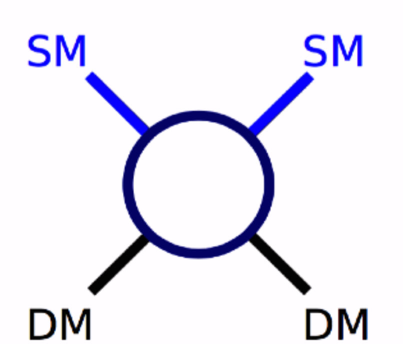
- stable **TeV-scale** particle with **weak-force-sized** interactions
  - Weakly Interacting Massive Particle (**WIMP**)…
  - …conveniently appearing in models that also solve other problems in particle physics (e.g. supersymmetry)
  - Beautiful and simple, almost *miraculous!*

Experimental advantage: many experiments can detect it in different ways

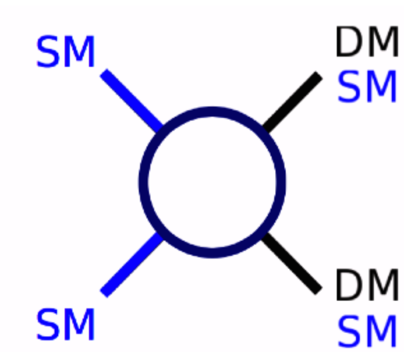
complementary discoveries



Indirect Detection

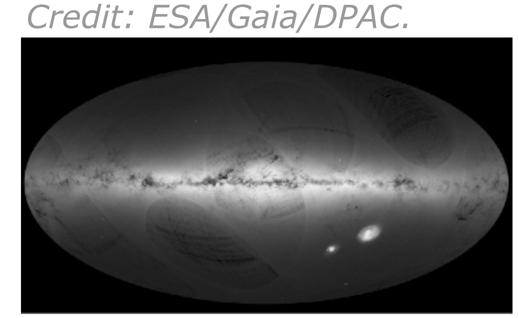


Direct Detection

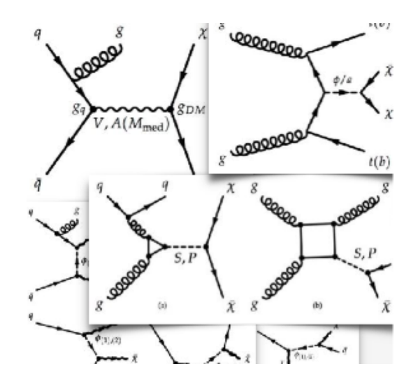


Colliders/ Accelerators

Credit: ESA/Gaia/DPAC.



Astrophysics



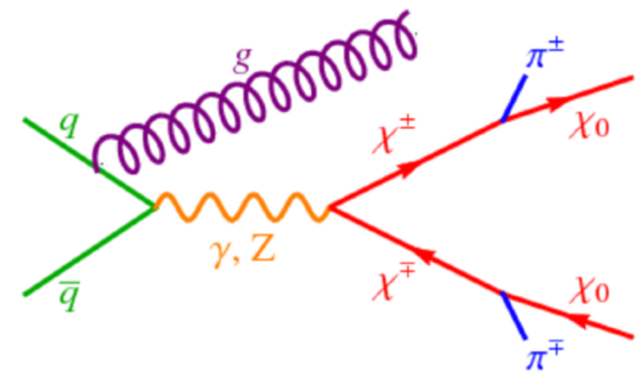
Theory input always necessary to contextualize

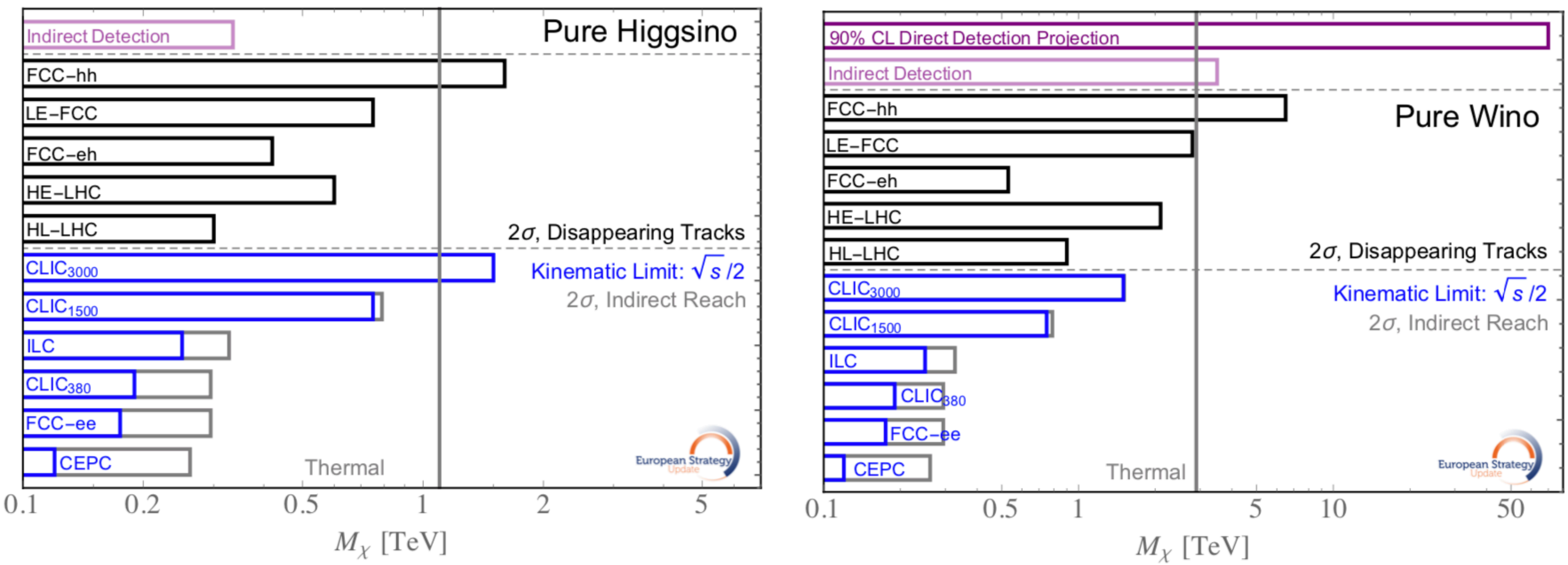
Pure Wino and Higgsino DM

European Strategy Update Briefing Book

arXiv:1802.04097, arXiv:0706.4071, arXiv:1705.04843

- Viable thermal relic WIMP candidate in SUSY terms: lightest neutralino - pure Wino/Higgsino
  - Also standalone model of "minimal DM"





Recent news on Wino and Higgsino

SnowMass2021

Wino & Higgsino at muon colliders

EF10 Focus Topic #1: **WIMPs**

https://arxiv.org/abs/2107.09688

Speakers at EF10 Parallel Session H: Marco Costa, Jose Francisco Zurita talk link

Considering **pure WIMP scenarios** where the EW interaction sets the relic (mass as a free parameter) and DM is the neutral component of a multiplet

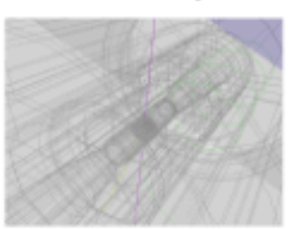
Many different signatures for WIMPs @ muon colliders in new literature / recent workshops:

- Recoil against visible objects
- Resonances from the DM particle bound states, which can be excited as a resonance and decay into visible particles
- Disappearing tracks (DT)

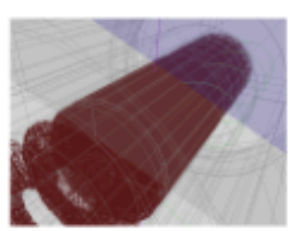
Results can be put into context of direct and indirect detection (esp. CTA projections)

"Lessons learned" from studies that can be brought back to AF:

- Beam background is significant at muon colliders

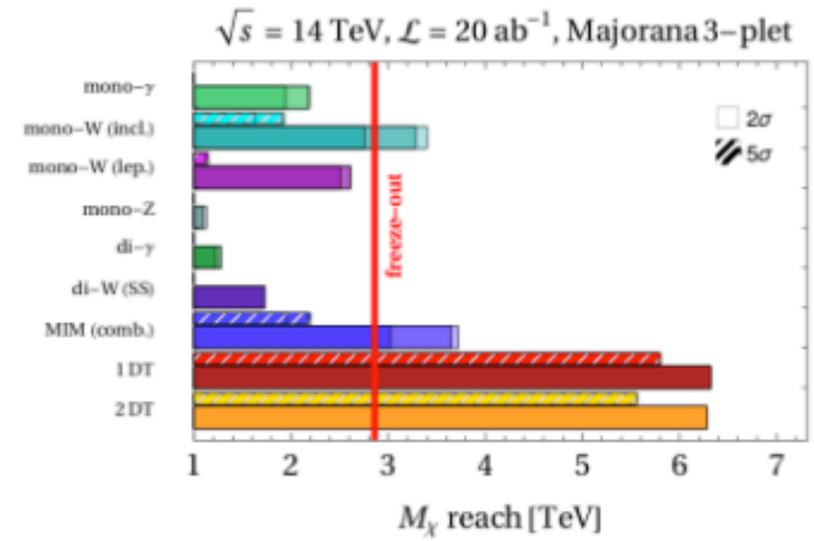


BIB off

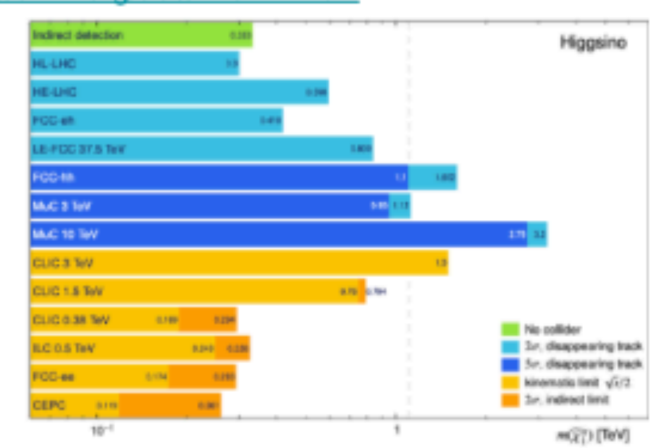


BIB on

Credit: F. Meloni



https://arxiv.org/abs/2102.11292



Message for EF10 whitepaper: a muon collider is competitive with FCC-hh for thermal WIMP scenarios

Complementarity message: muon collider results can lead to joint WIMP discoveries with DD and ID

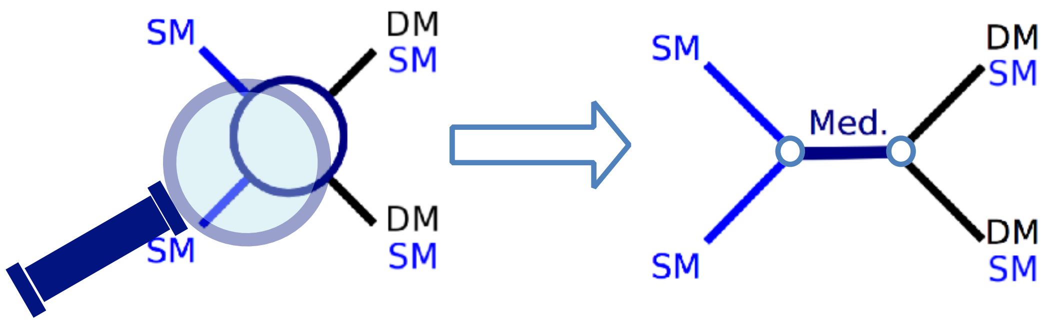
11

Caterina Doglioni & Liantao Wang - EF10 - 2021/03/09 Snowmass EF Restart Workshop

Other benchmarks for collider WIMP searches

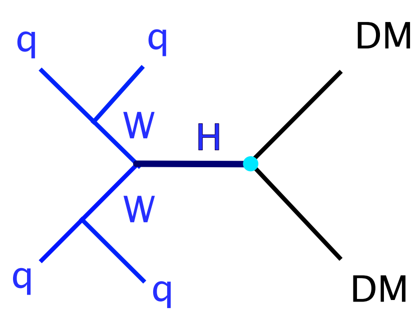
Simple models ⟷ More complex/complete models

Simple DM mediation



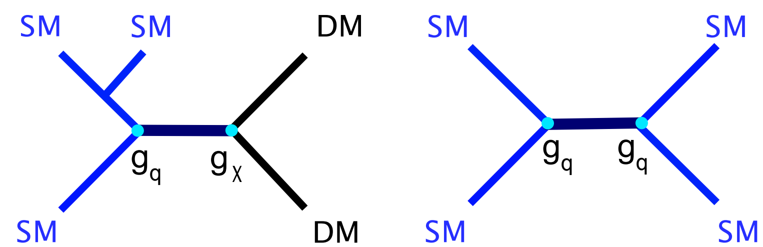
SM mediator

- **Z/Higgs** portals



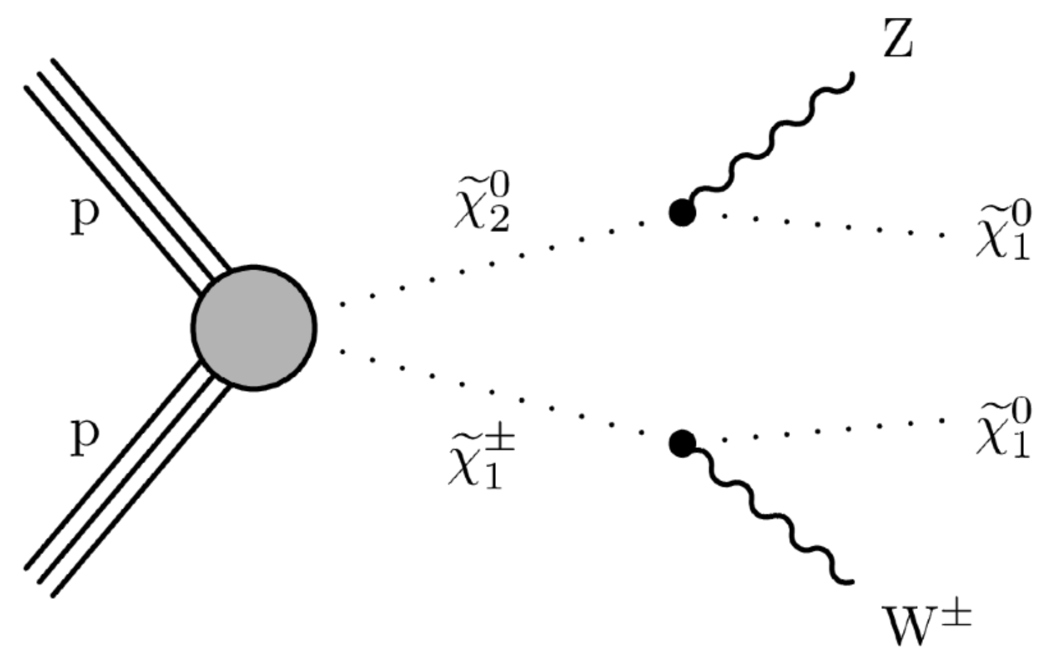
Beyond-SM mediator

- **Vector-like** mediator



- **Scalar-like** mediator and Two Higgs Doublet Models

Supersymmetry



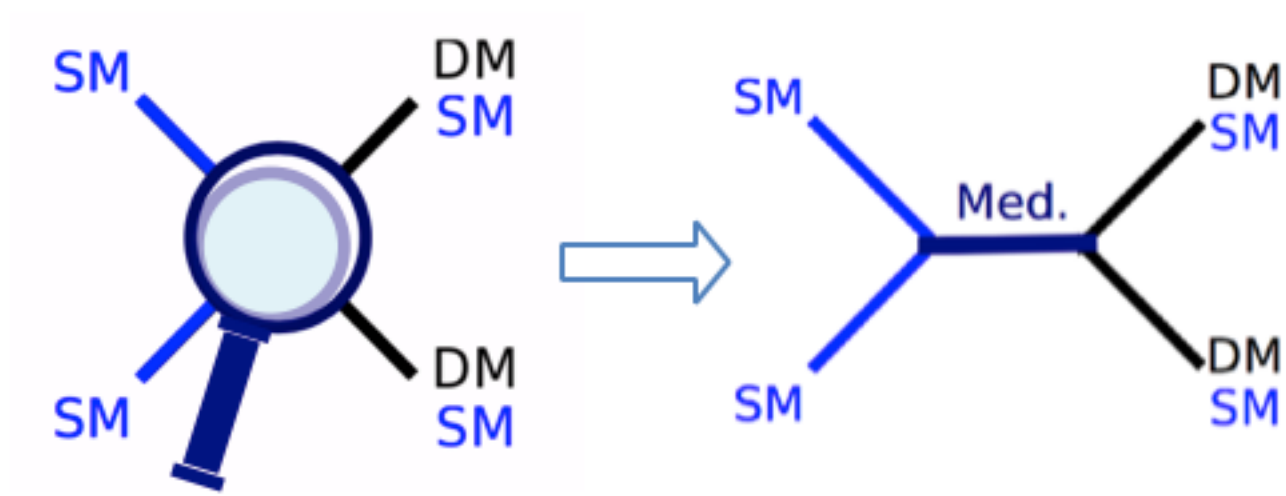
(*Simplified model* diagram)

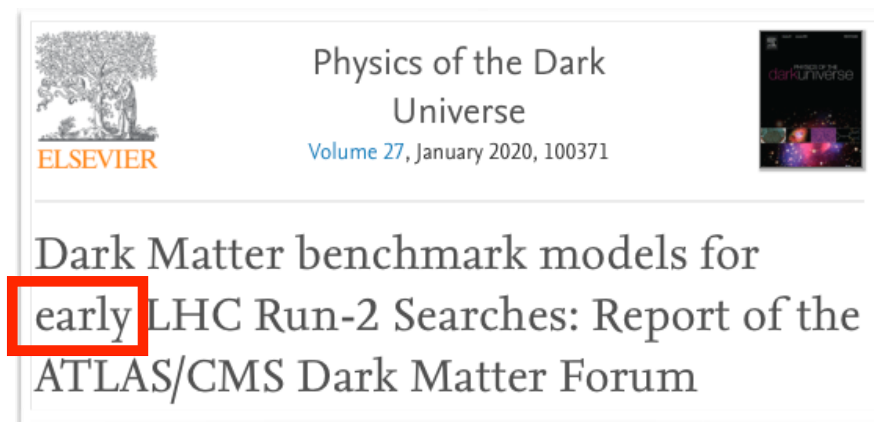
JHEP 03 (2018) 160

Also: DM models with long-lived particles

Dark Matter mediators at the LHC

If there's a force other than gravity, there's a **mediator**,
and colliders could **detect** it via its **visible decays**:
(WIMP) *simplified models* have been popular Run-2 LHC search benchmarks

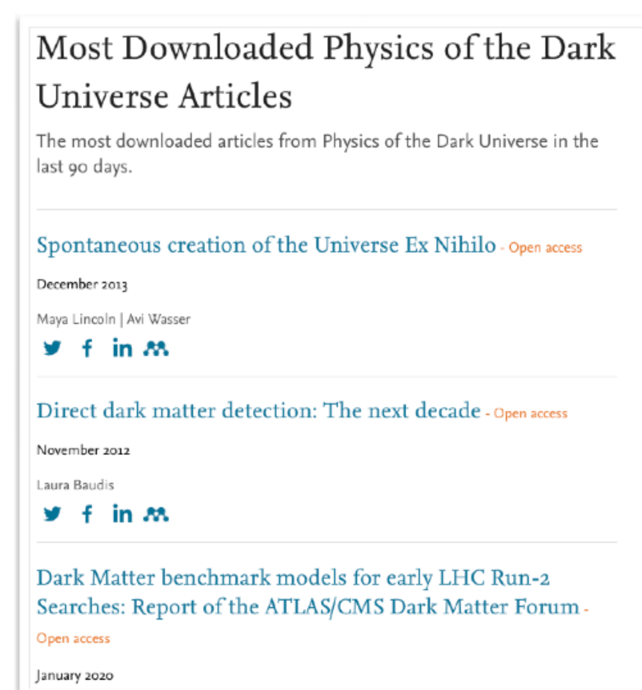



ELSEVIER

Physics of the Dark Universe

Volume 27, January 2020, 100371

Dark Matter benchmark models for early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum


Most Downloaded Physics of the Dark Universe Articles

The most downloaded articles from Physics of the Dark Universe in the last 90 days.

Spontaneous creation of the Universe Ex Nihilo - Open access

December 2013

Maya Lincoln | Avi Wasser

Direct dark matter detection: The next decade - Open access

November 2012

Laura Baudis

Dark Matter benchmark models for early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum - Open access

January 2020

Dark Matter Forum & Working Group

https://lpcc.web.cern.ch/content/lhc-dm-wg-dark-matter-searches-lhc
Phys. Dark Univ. 26 (2019) 100371 & references within
Ann Rev Nucl Part Sci Vol. 68:429-459, 2018 for a LHC review

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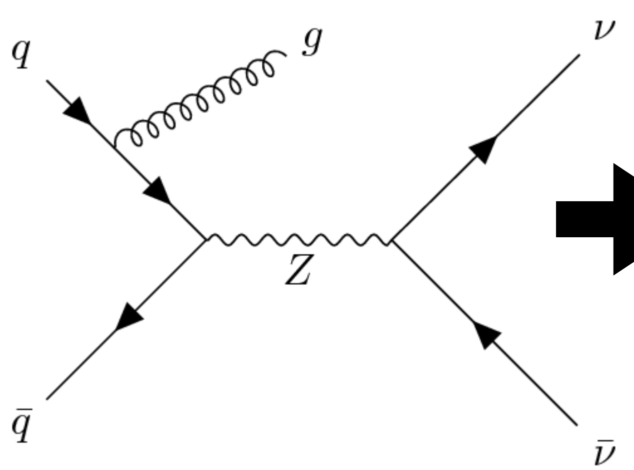
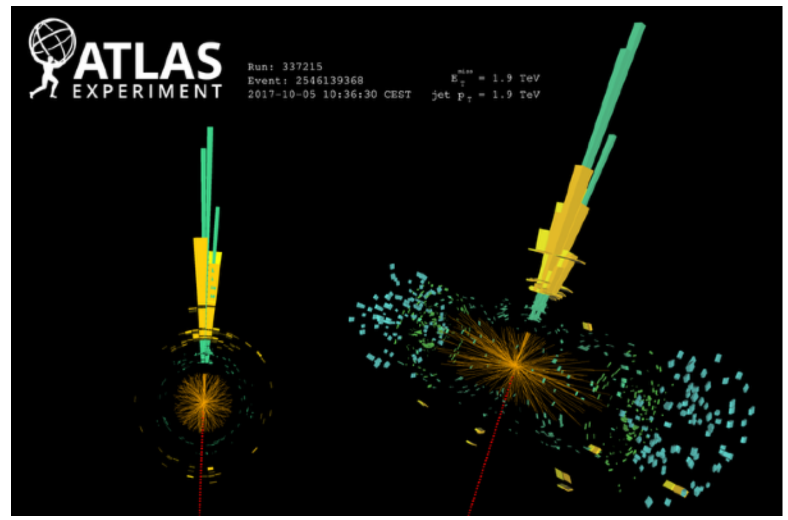
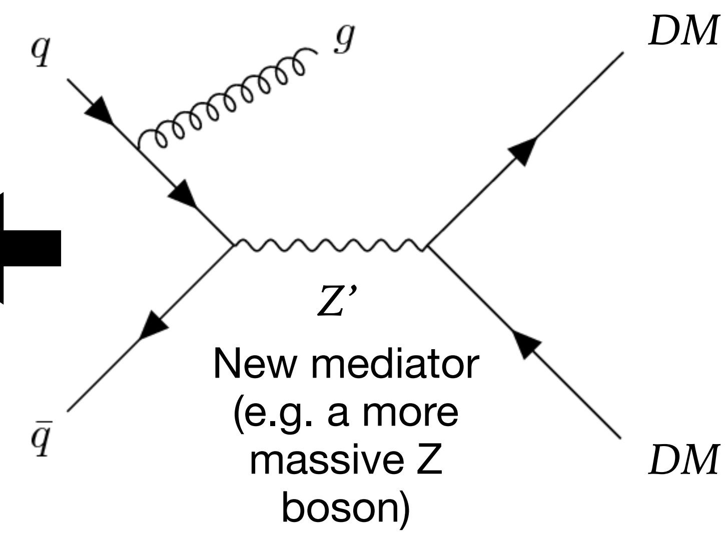
A generic search for WIMP DM: "*X+MET*"

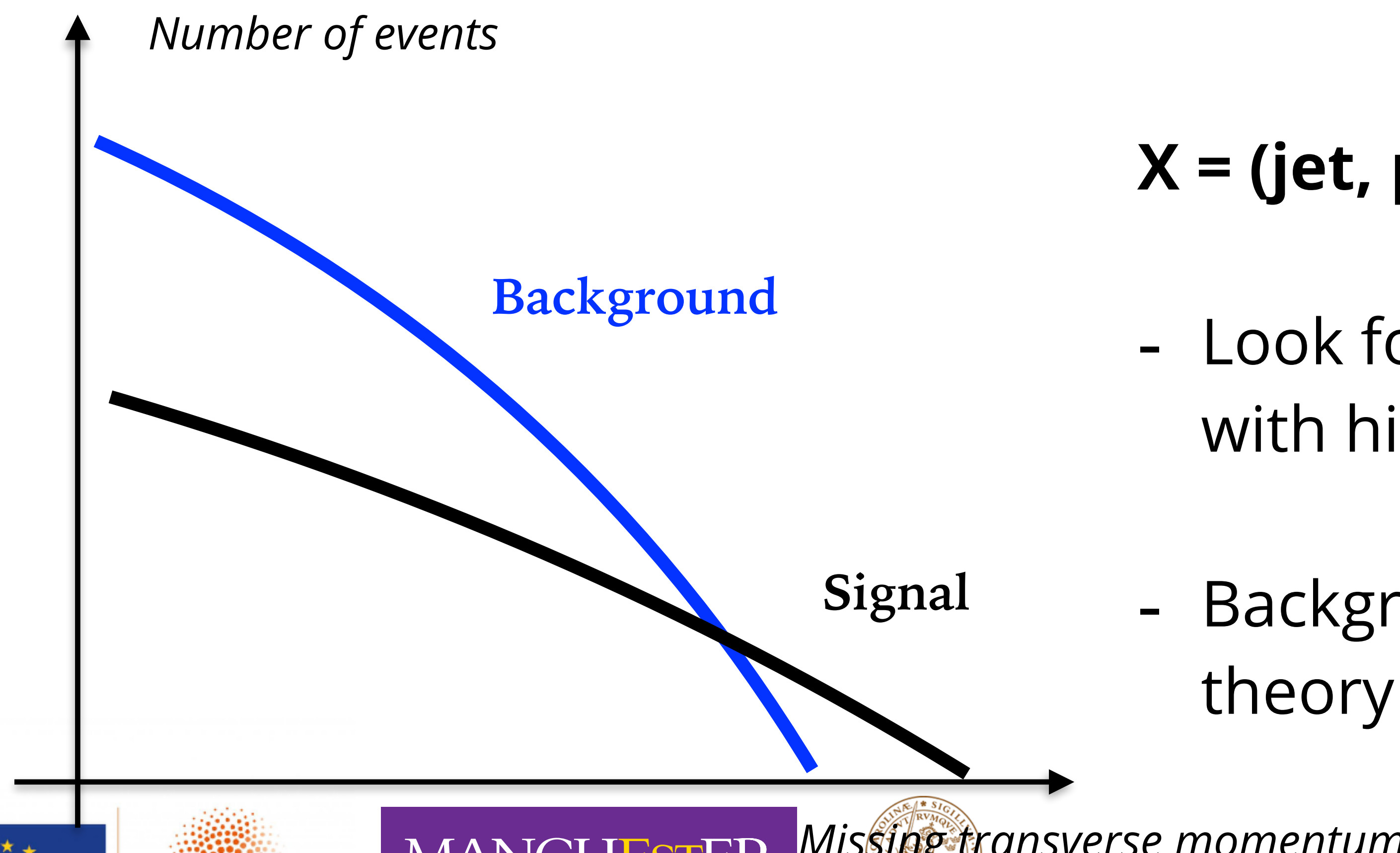
Background (frequent)





Signal (rare)



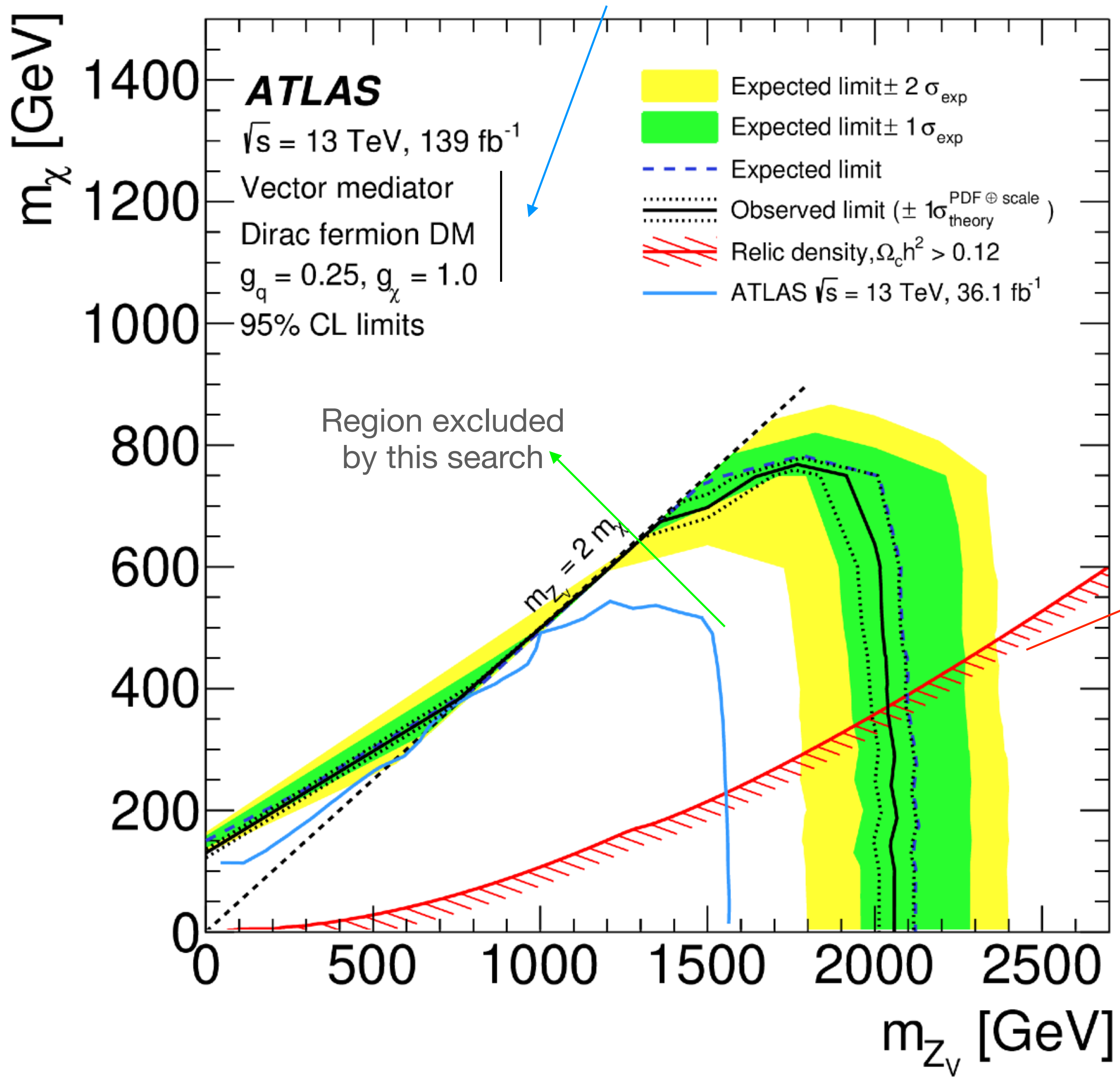


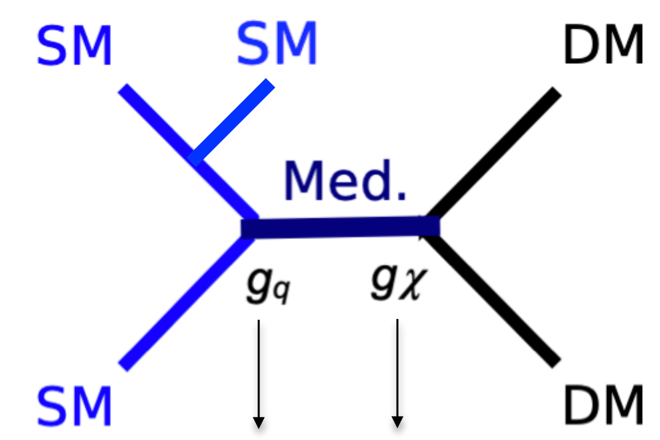
X = (jet, photon, W/Z boson...) + MET search

- Look for an excess of events with high MET over the SM background
- Background shapes need precise theory predictions (*precision search*) EPJC 2017 77:829

A DM interpretation of LHC jet+MET search

arXiv:2102.10874 Model assumptions - more models can be/are tested



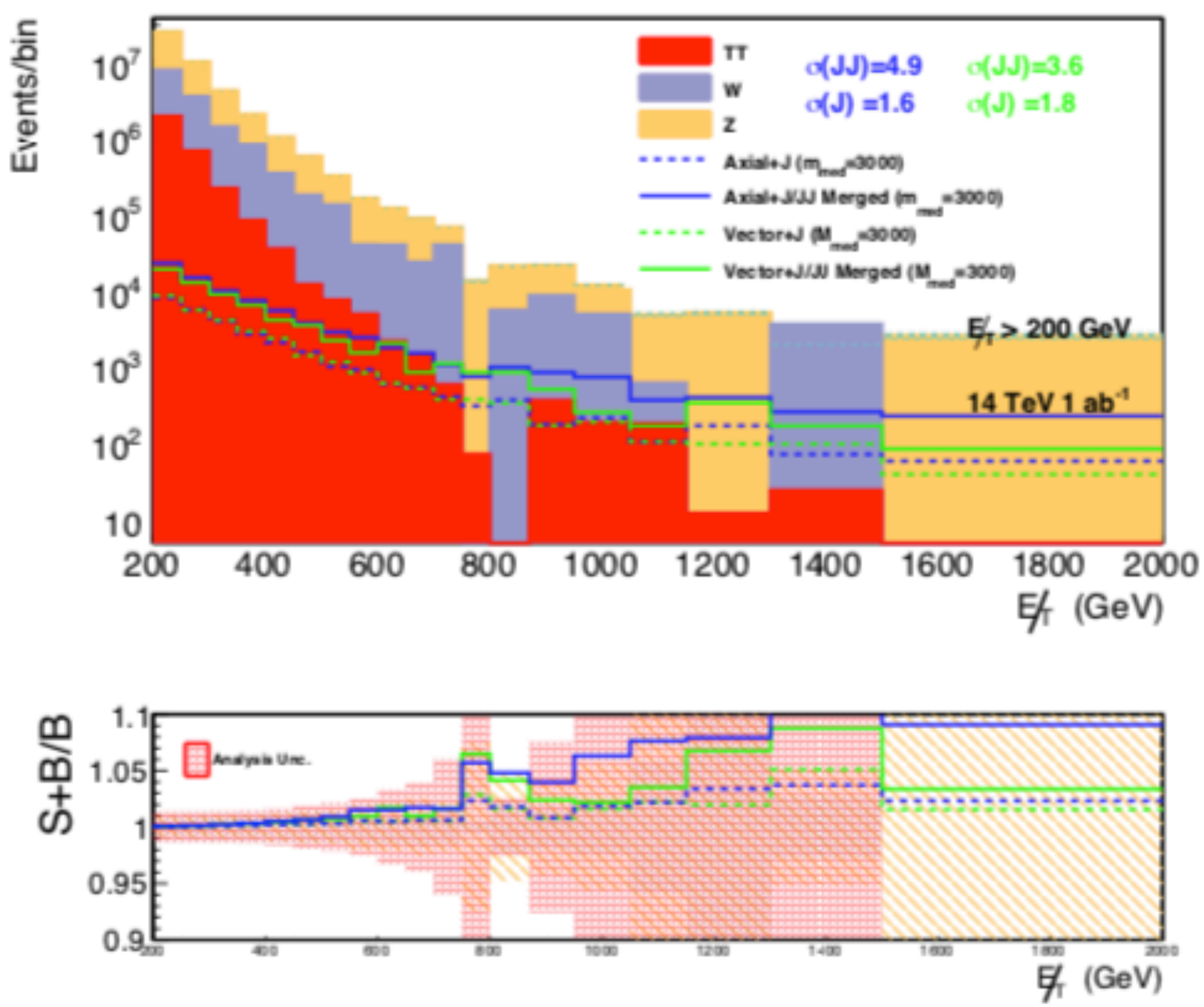


Strengths of the interaction (=coupling) mediator-quarks and mediator-DM

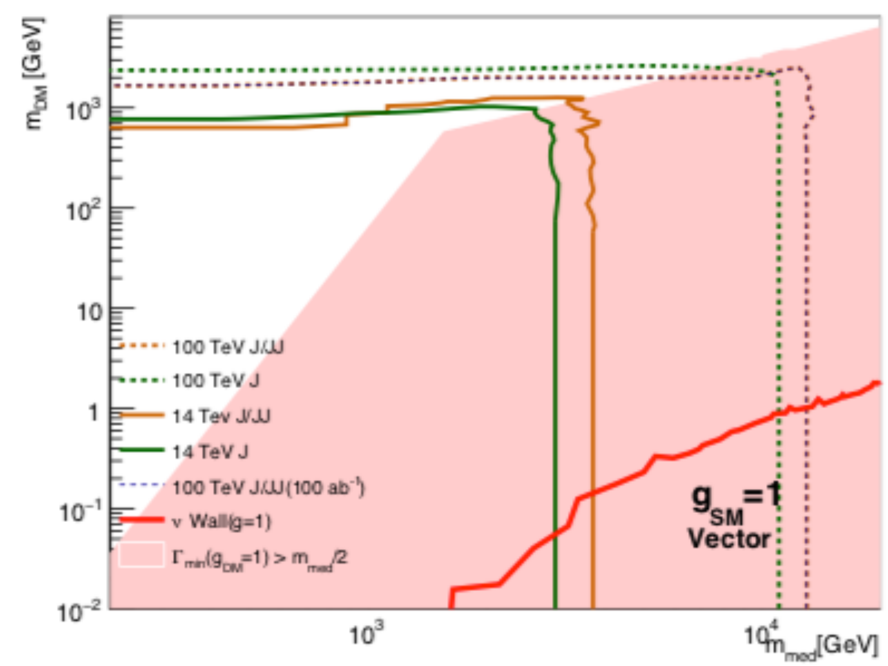
Other interpretations:

- Different kinds of mediators
- Supersymmetric models
- Extra dimensions
- Axion-like particles

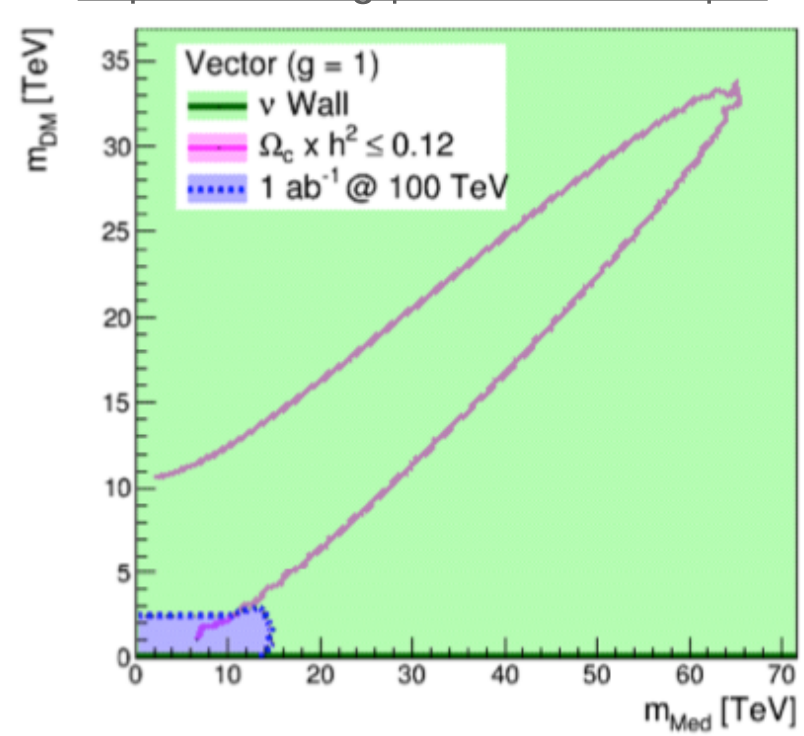
A DM interpretation of FCC-hh jet+MET search



https://arxiv.org/pdf/1606.00947.pdf



https://arxiv.org/pdf/1603.08525.pdf



Details in this talk by Phil Harris

To fit the background, **precision information needed on**

- NLO corrections for main backgrounds
- Parton Distribution Functions (See S. Camarda's talk on Tuesday)

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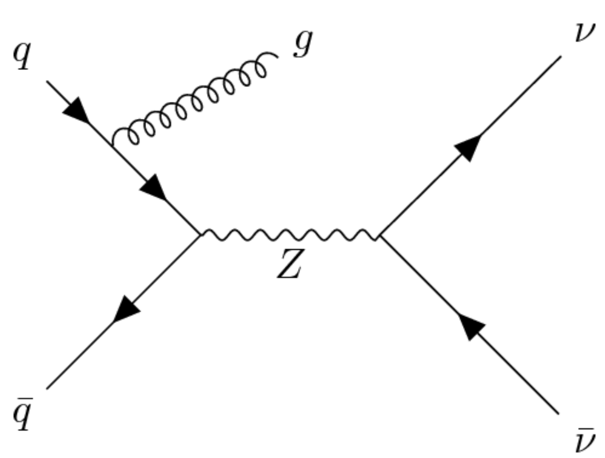
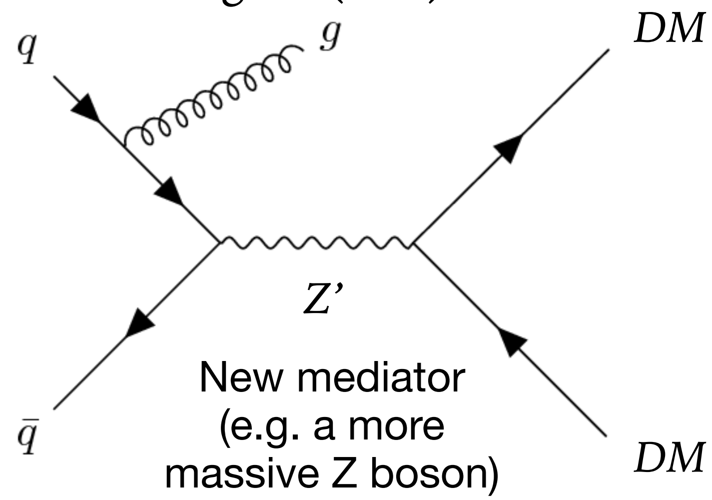
Parallels: visible and invisible mediator-based searches

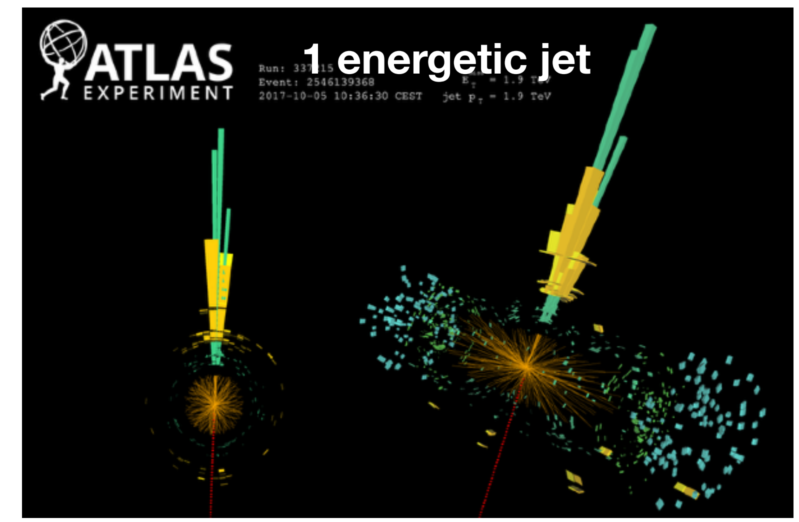
Detection of **DM** (invisible particles) **from a mediator**

Background (frequent)



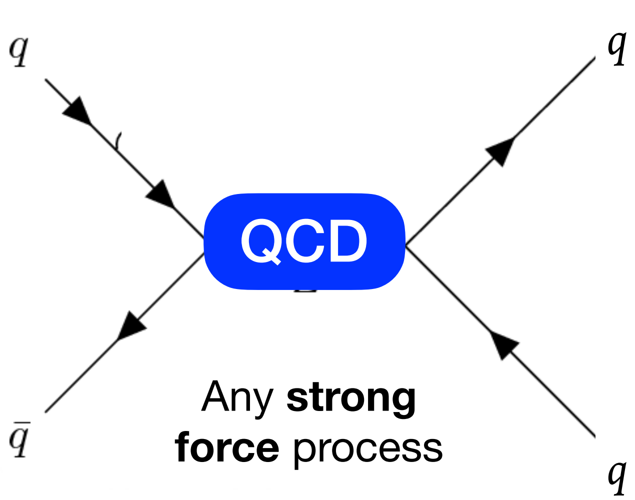
Signal (rare)



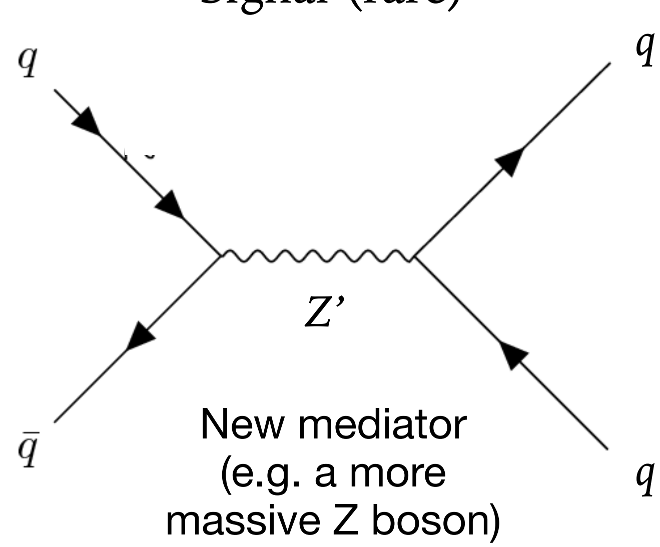


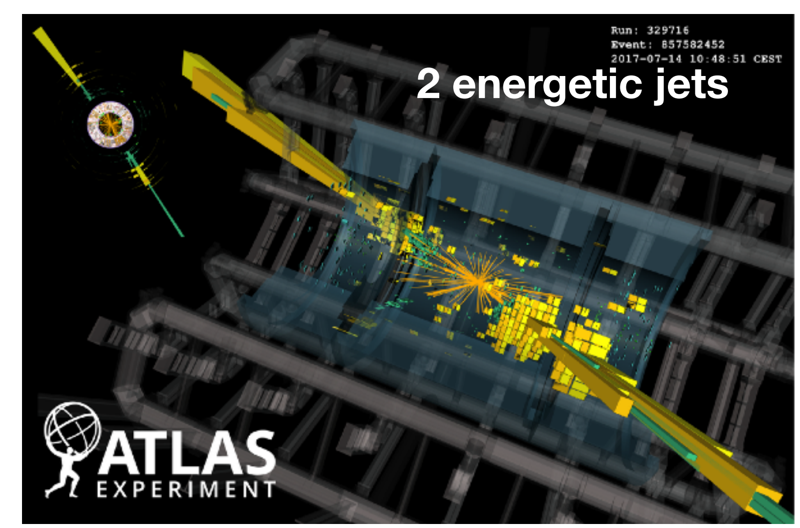
Detection of the DM **mediator**, via its **visible** (hadronic) **decays**:

Background (very frequent)



Signal (rare)





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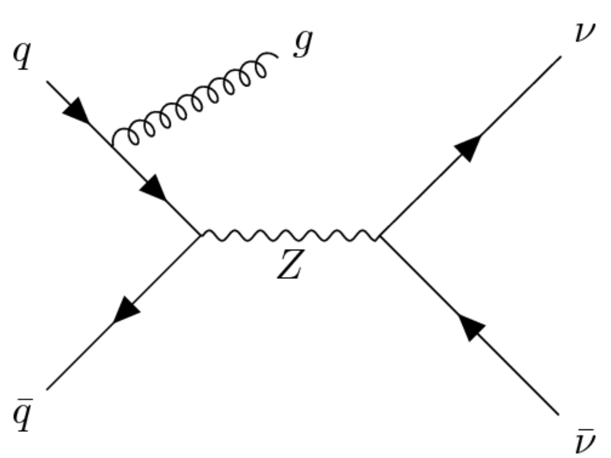
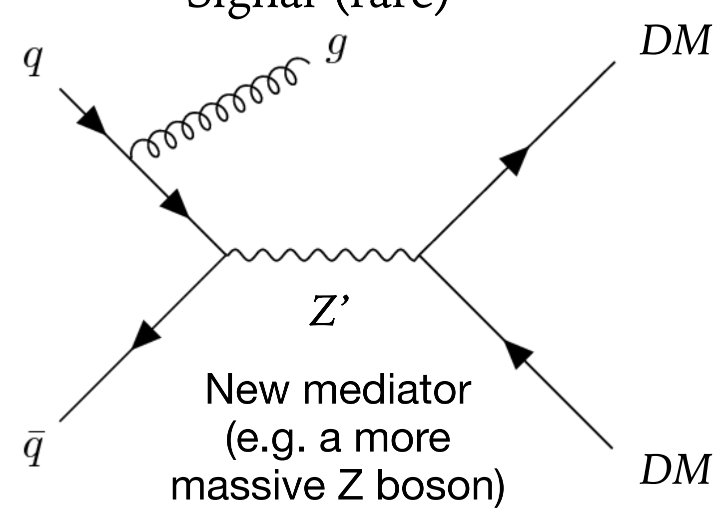
Parallels: visible and invisible mediator-based searches

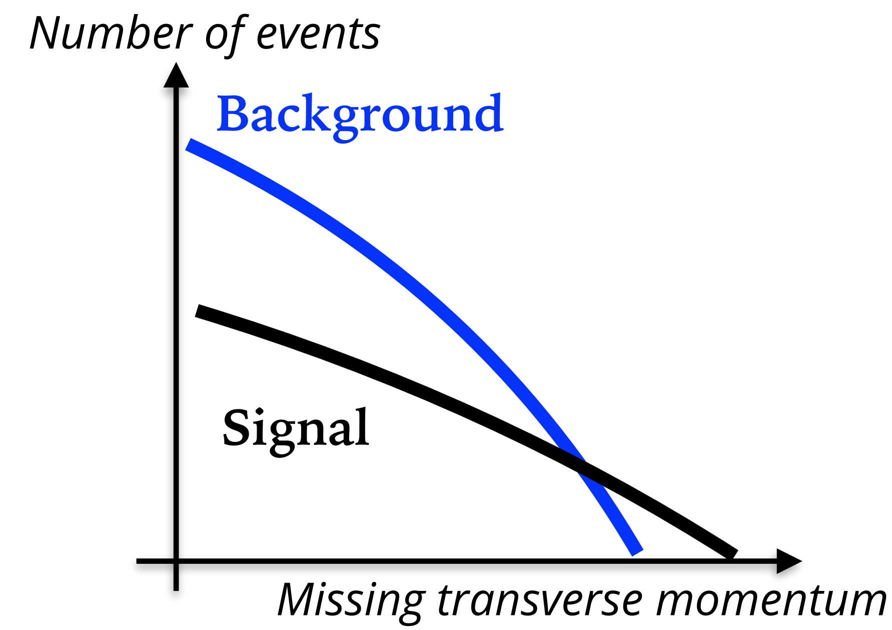
Detection of **DM** (invisible particles) **from a mediator**

Background (frequent)



Signal (rare)





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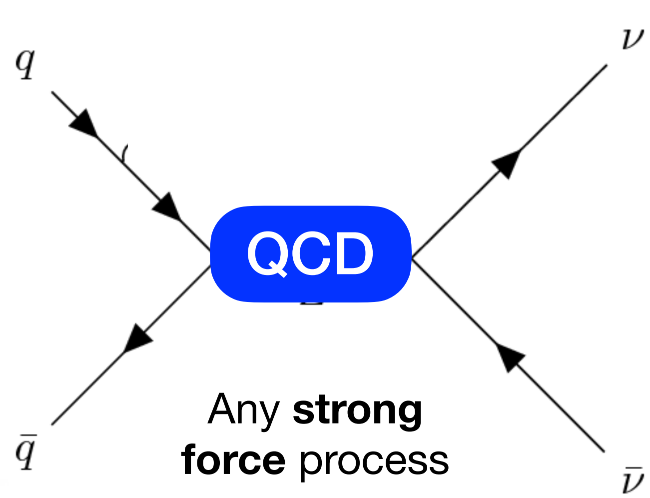
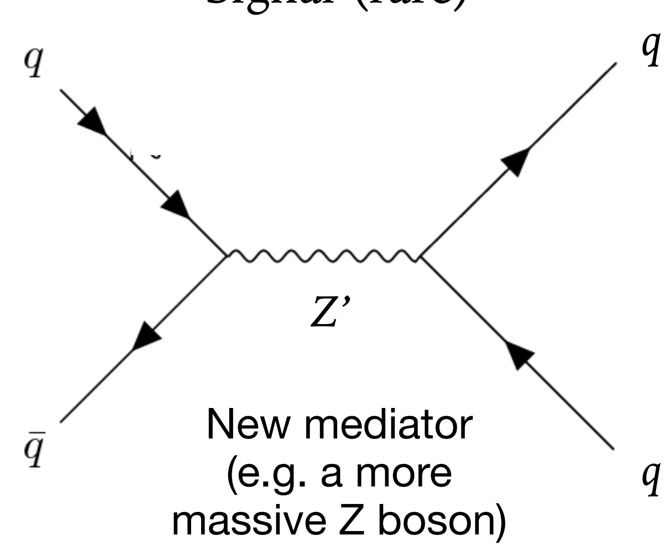
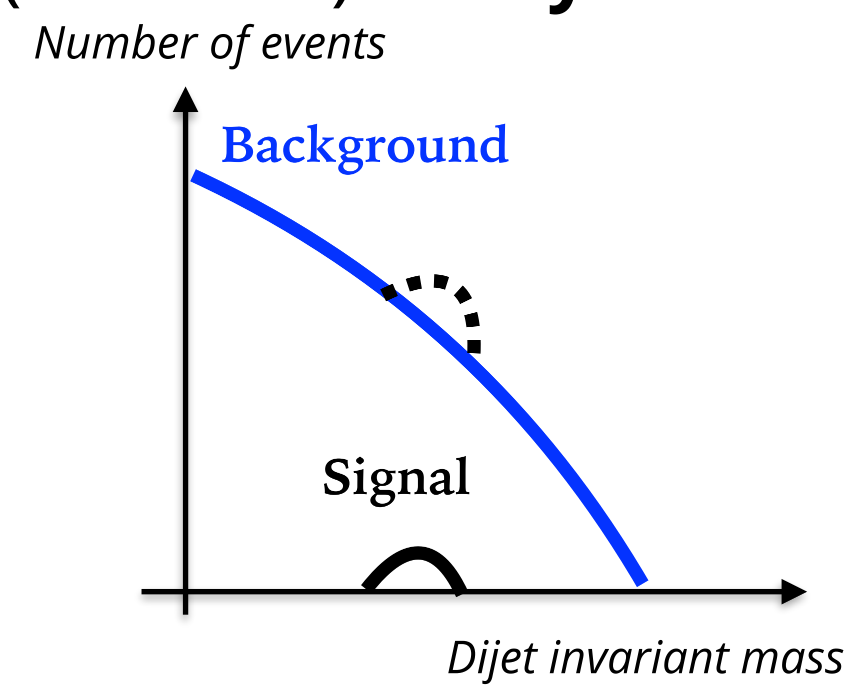


Signal (rare)

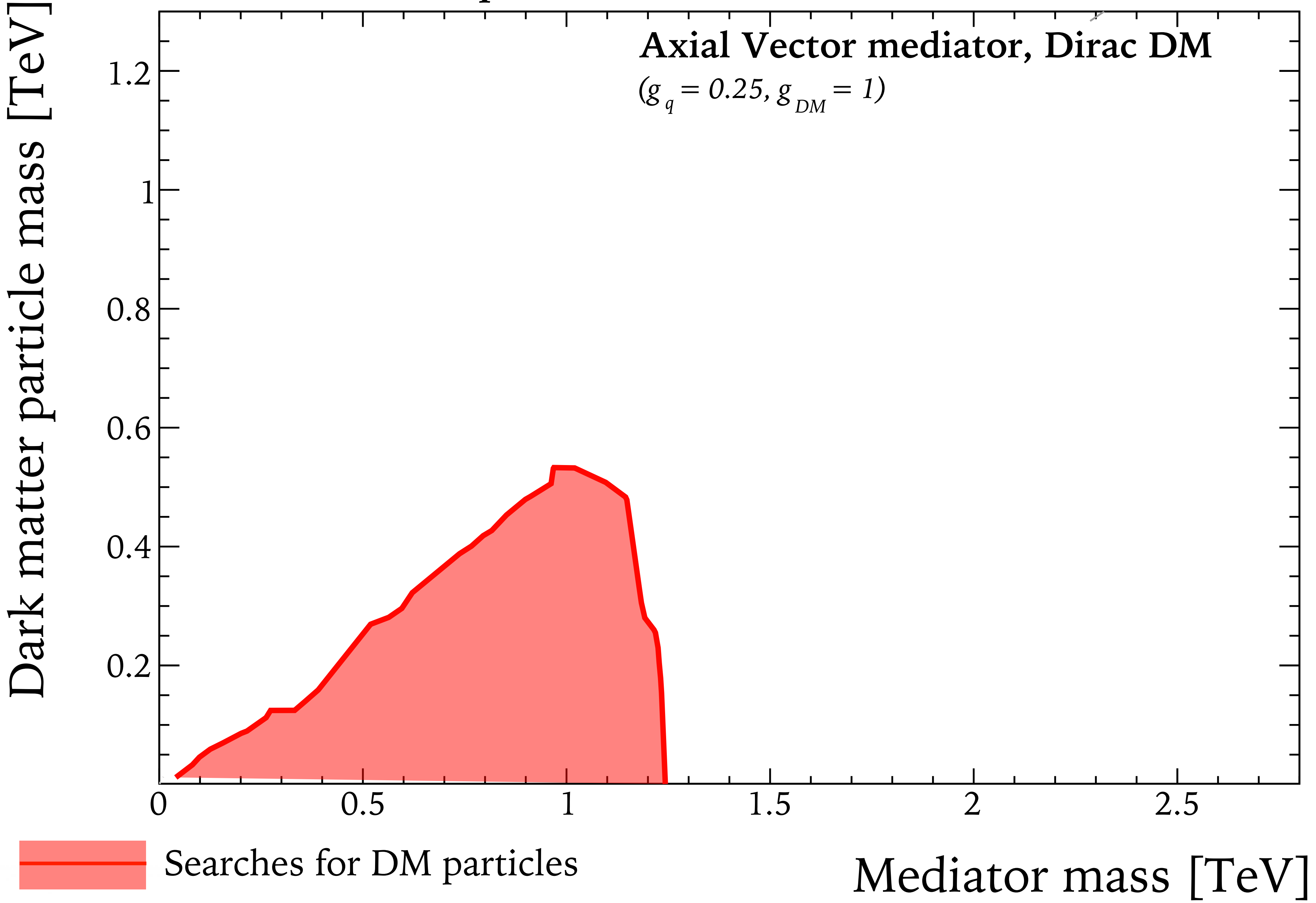




Complementarity of visible/invisible searches

Illustrative example

LHC Dark Matter Working Group
Phys. Dark. Univ. 26 100377 (2019)



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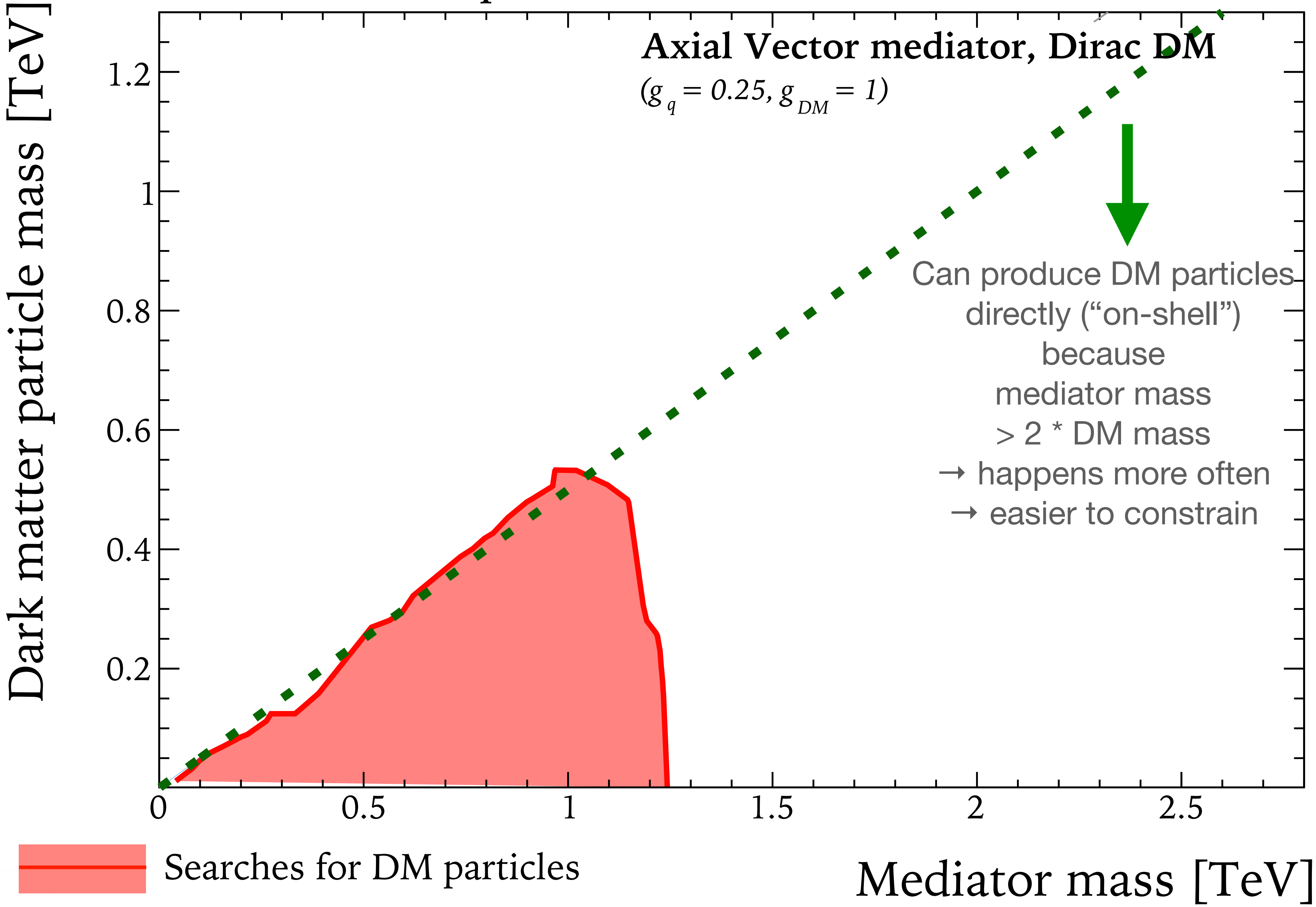

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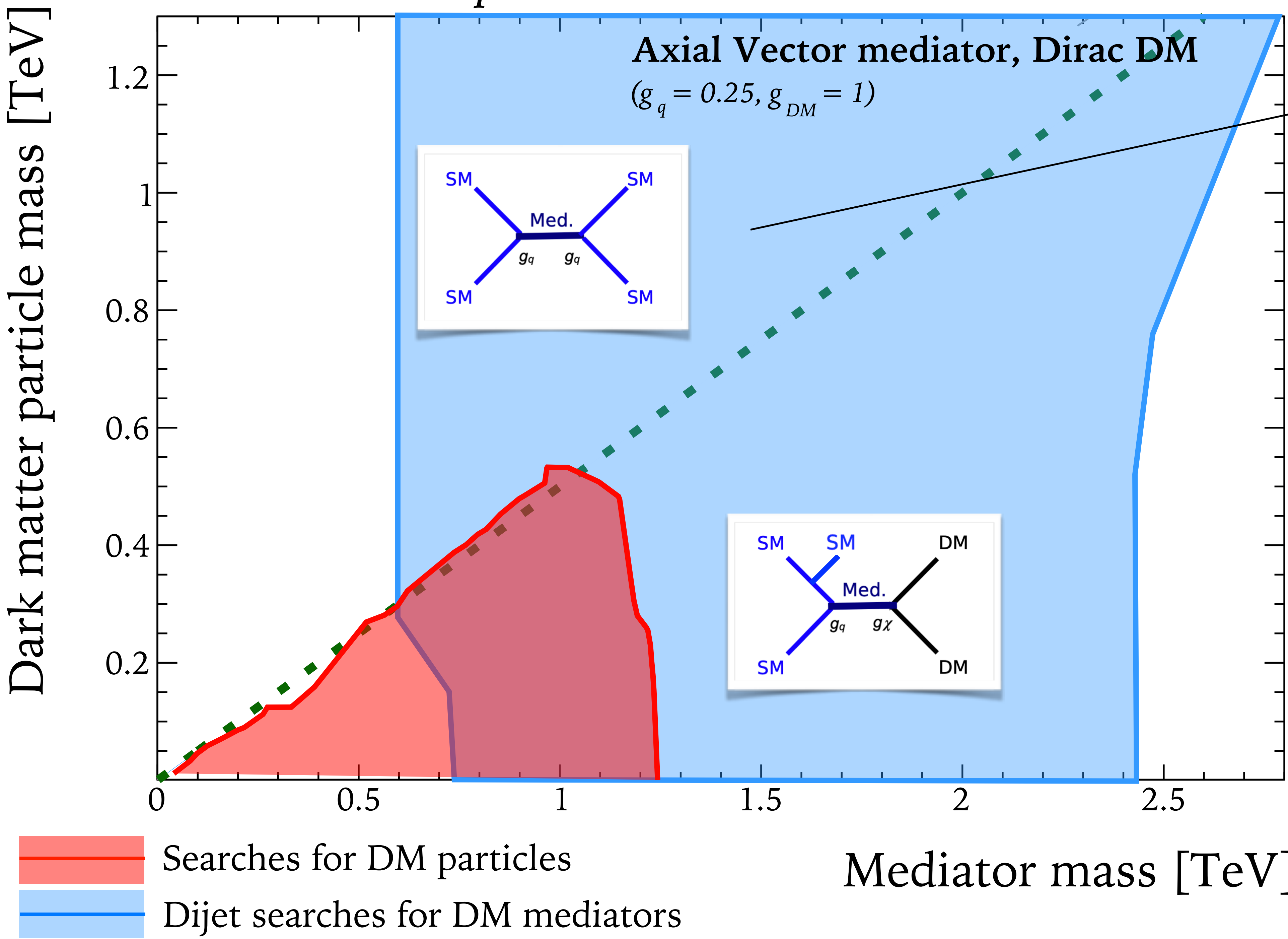


For mediator decays into quarks, the DM mass isn't too relevant (especially when they dominate)

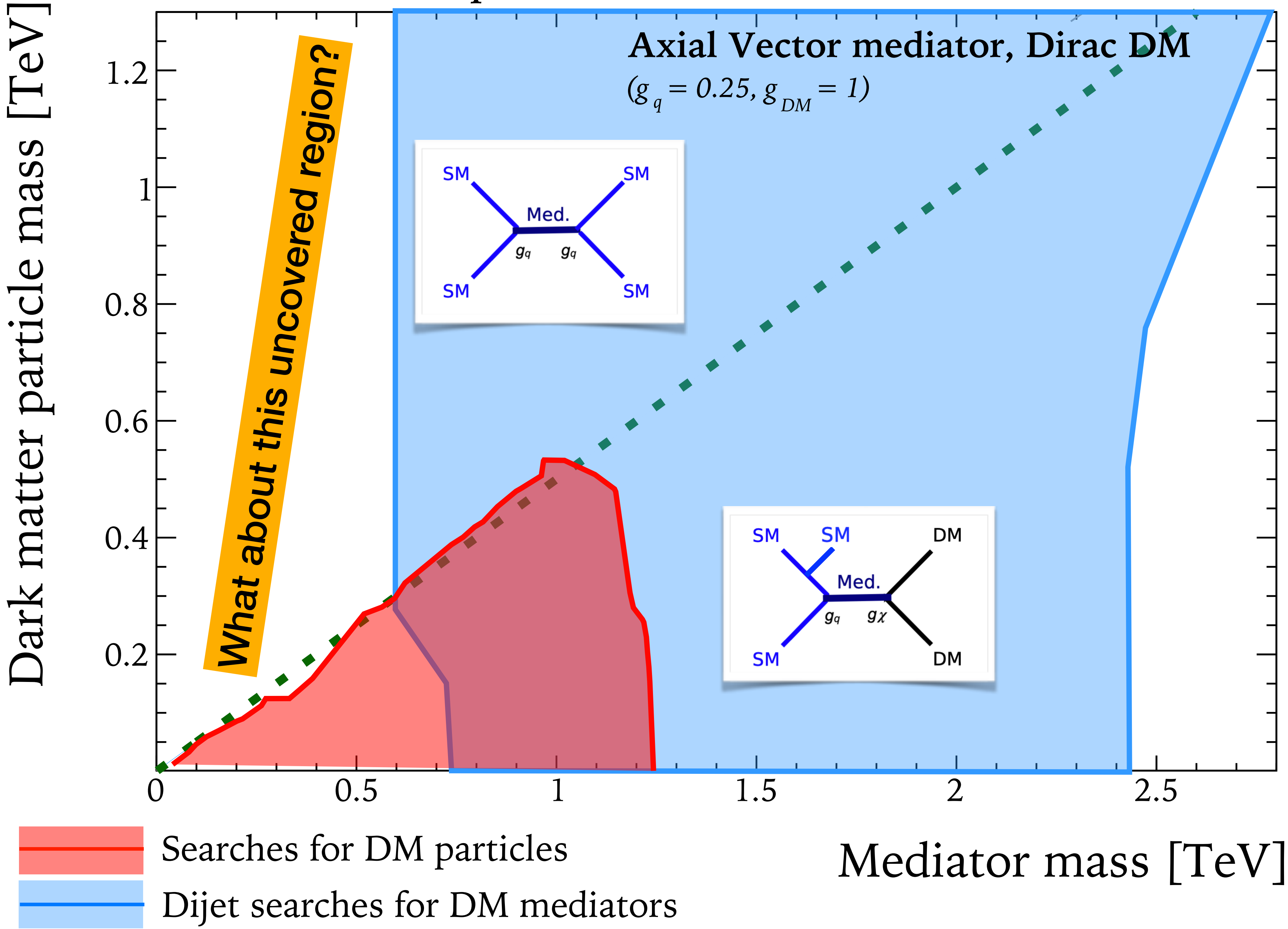
Possible to constrain the parameter space even if DM is too heavy to be produced at the LHC

However, we need a connection between a dijet discovery and a DM discovery… *more later!*

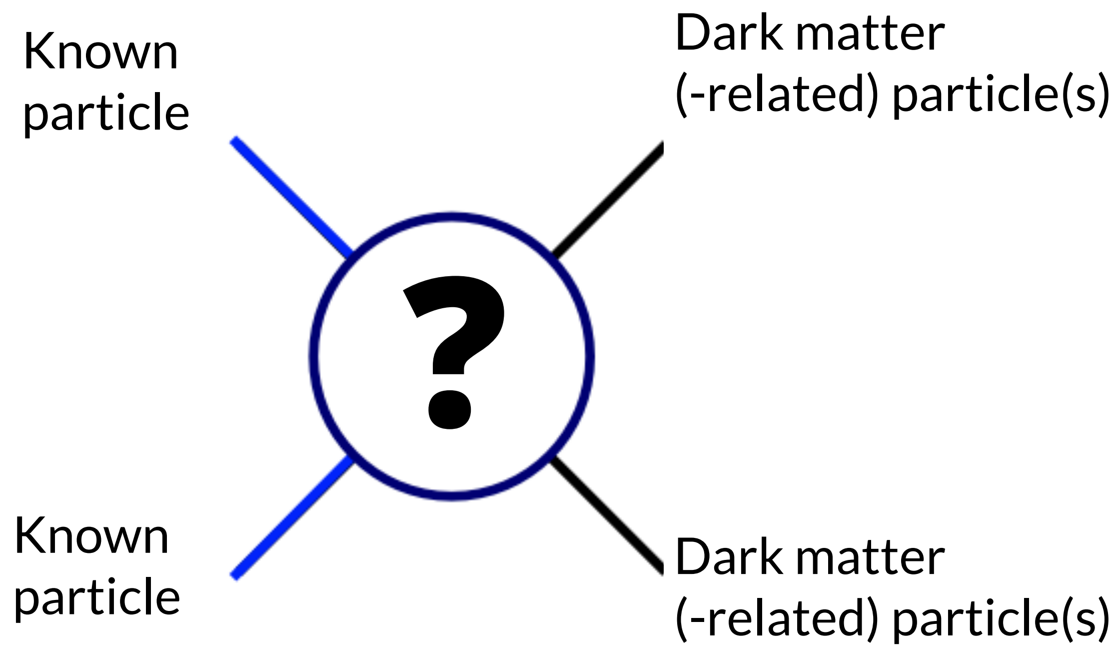
Complementarity of visible/invisible searches

Illustrative example

LHC Dark Matter Working Group
[Phys. Dark. Univ. 26 100377 (2019)]



Recreating dark matter/dark sectors in the lab: challenges



Trying to stay as **model-agnostic** as possible, while exploiting what the **LHC** is good at: focus on the presence of a **resonance** (alongside EFTs/more complete theories)

added bonus: resonance searches are bread&butter at colliders → robust analysis toolkit available

Challenges:

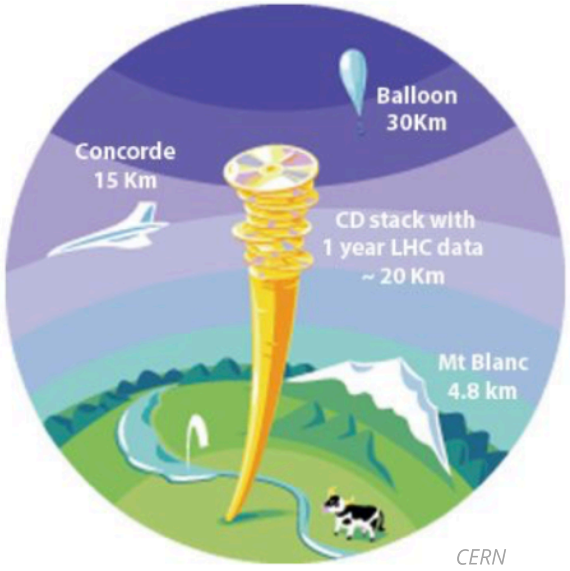
1. This kinds of processes are very **rare**
2. Many other processes may look the same (→large **backgrounds**)
3. Often **we don't know** how the resonance decays look like

These challenges can be met with non-standard analysis workflows!

A “Big Science” problem to solve: *too much data*

- The **dark matter signals** we are looking for are **rare**
  → need enormous amount of collisions to produce them
- Their **backgrounds** look the same and are **much larger**

- **Problem:** recording all LHC data takes 400000 PB/year [Ref]
  - up to 30 million proton-proton collisions/second (MHz)
  - ~ 1-1.5 MB/data per collision event, including raw data
- FCC-hh plans to collide beams up to every 5 ns (now: 25 ns)
  - and Moore’s law / storage costs don’t scale as fast as that yet



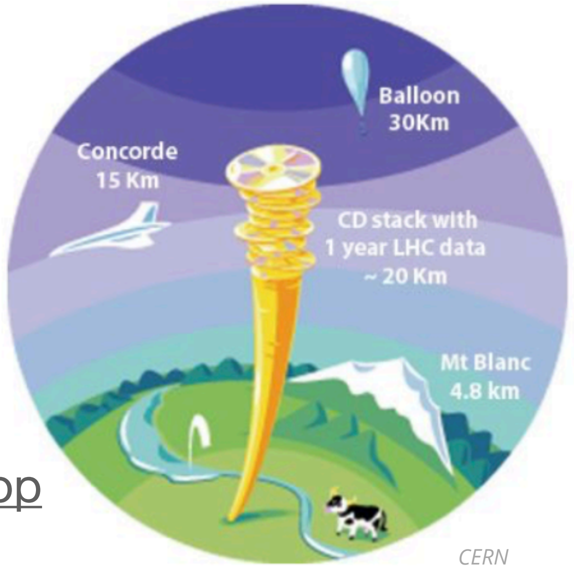
after selection of ”interesting” data

A "Big Science" problem to solve: *too much data*

- The **dark matter signals** we are looking for are **rare**
  → need enormous amount of collisions to produce them
- Their **backgrounds** look the same and are **much larger**

- **Problem:** recording all data would take too much space!

For other experimental requirements, see C. Vernieri's talk @ Snowmass EF Restart Workshop



CERN

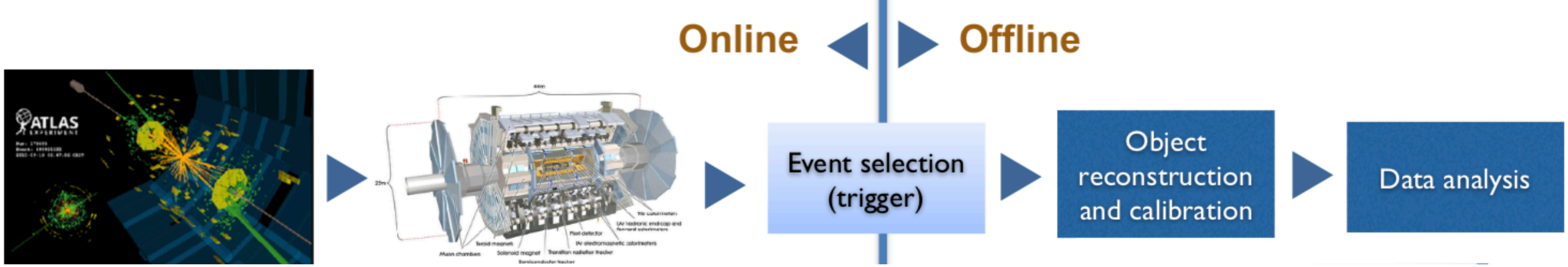
after selection of "interesting" data

LHC & future hadron collider experiments need to select "interesting" events (=*trigger*) **in real-time** (milli/microseconds)

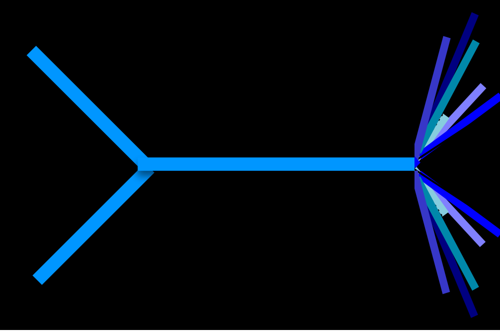
Collisions at ~30 MHz (~1 MB of info each)

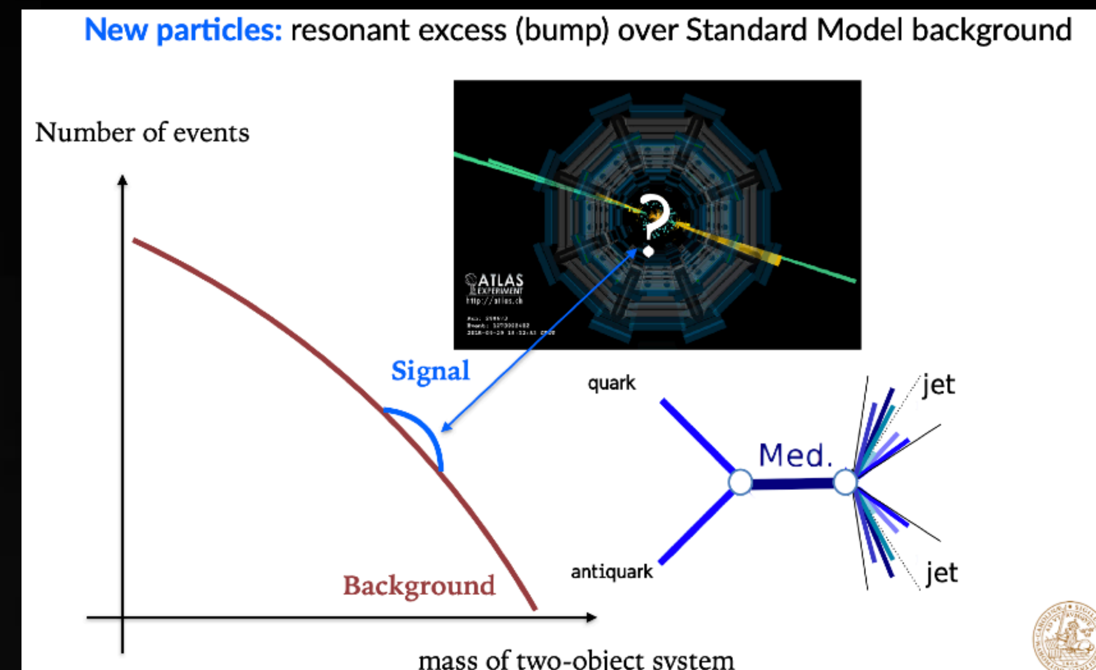
Hardware trigger outputs ~100 kHz

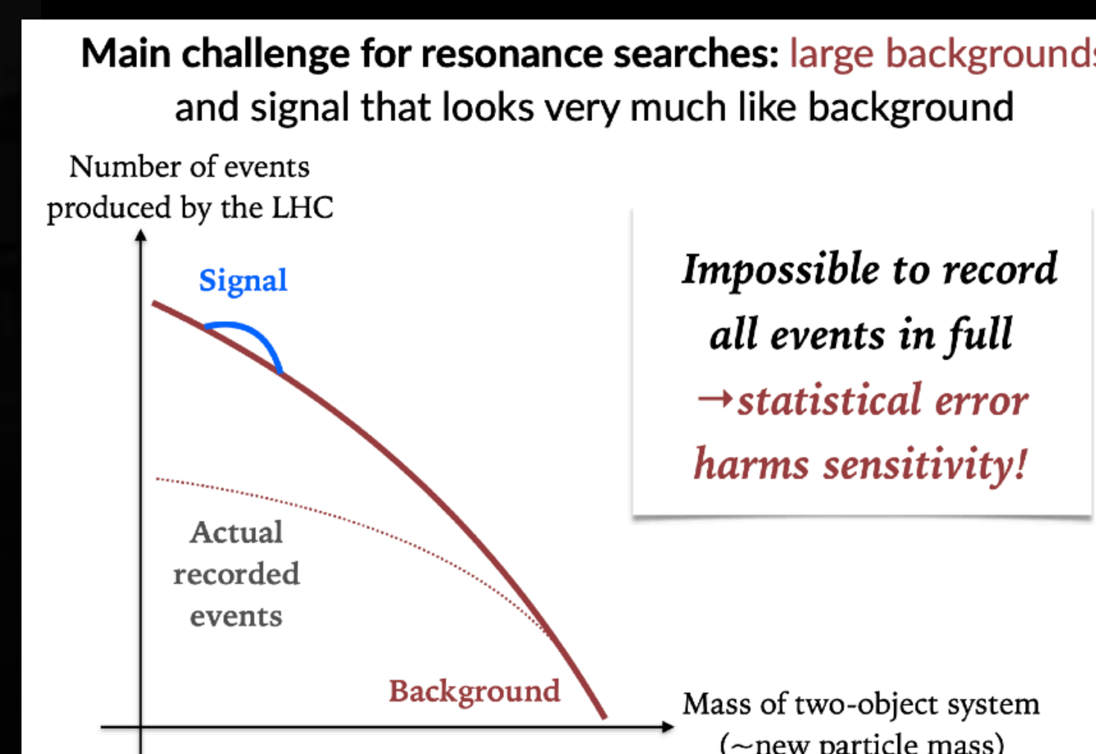
Software trigger outputs ~1 kHz



Are we missing rare hadronic processes?





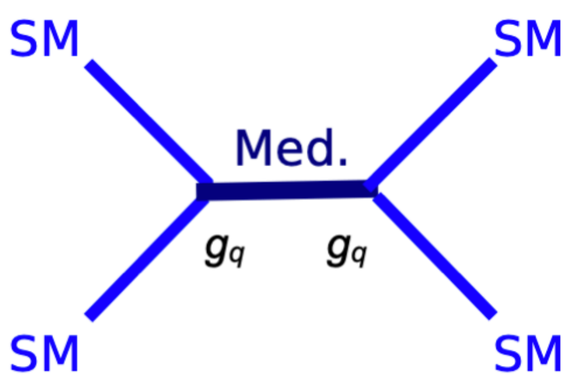


Events selected by the trigger

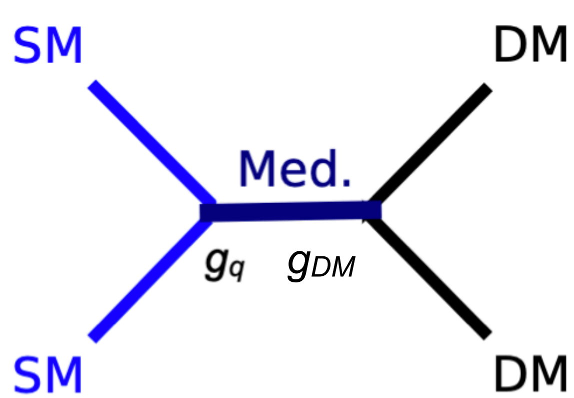
Example: dijet decays of DM mediators, ca 2013

Selecting interesting events works for most of the LHC physics program…
…but it is not optimal for rare processes with high-rate backgrounds:
we cannot record and store all data, and trigger discards both background and signal

This prevented us from being sensitive to low-mass DM mediators decaying into jets

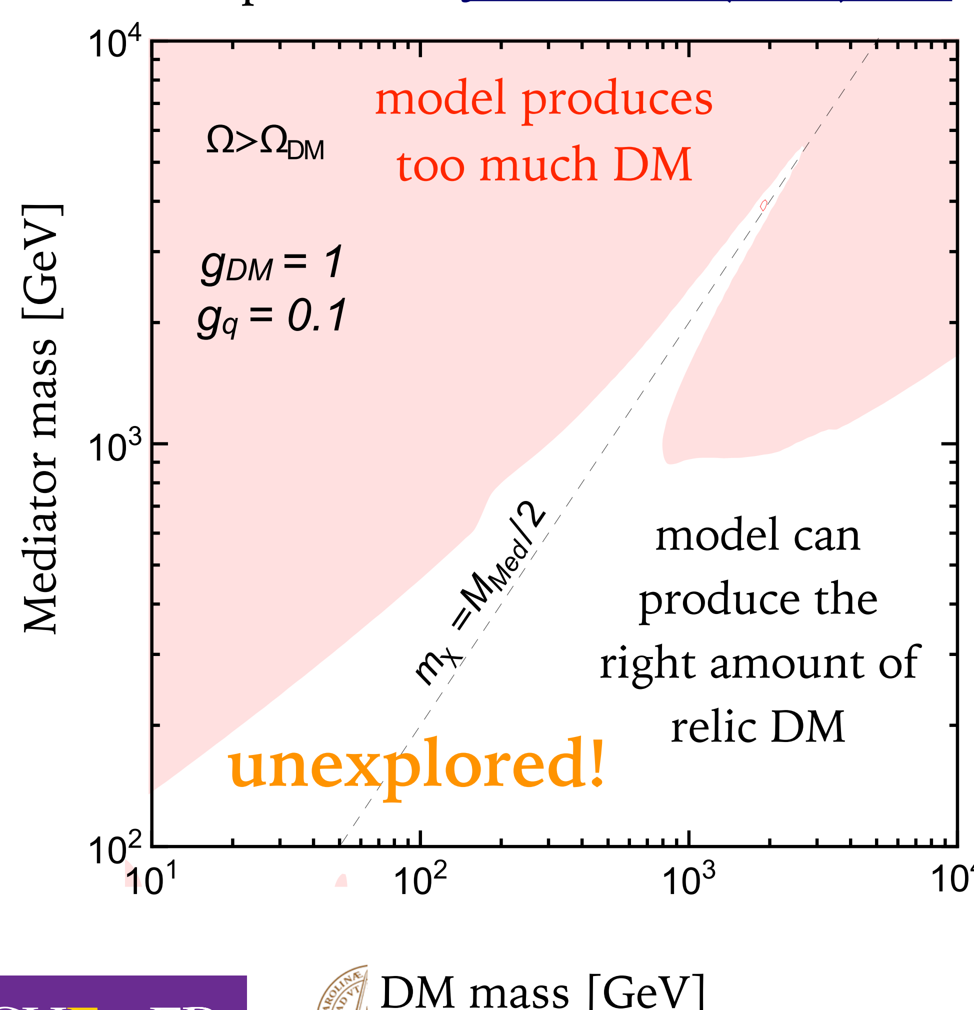


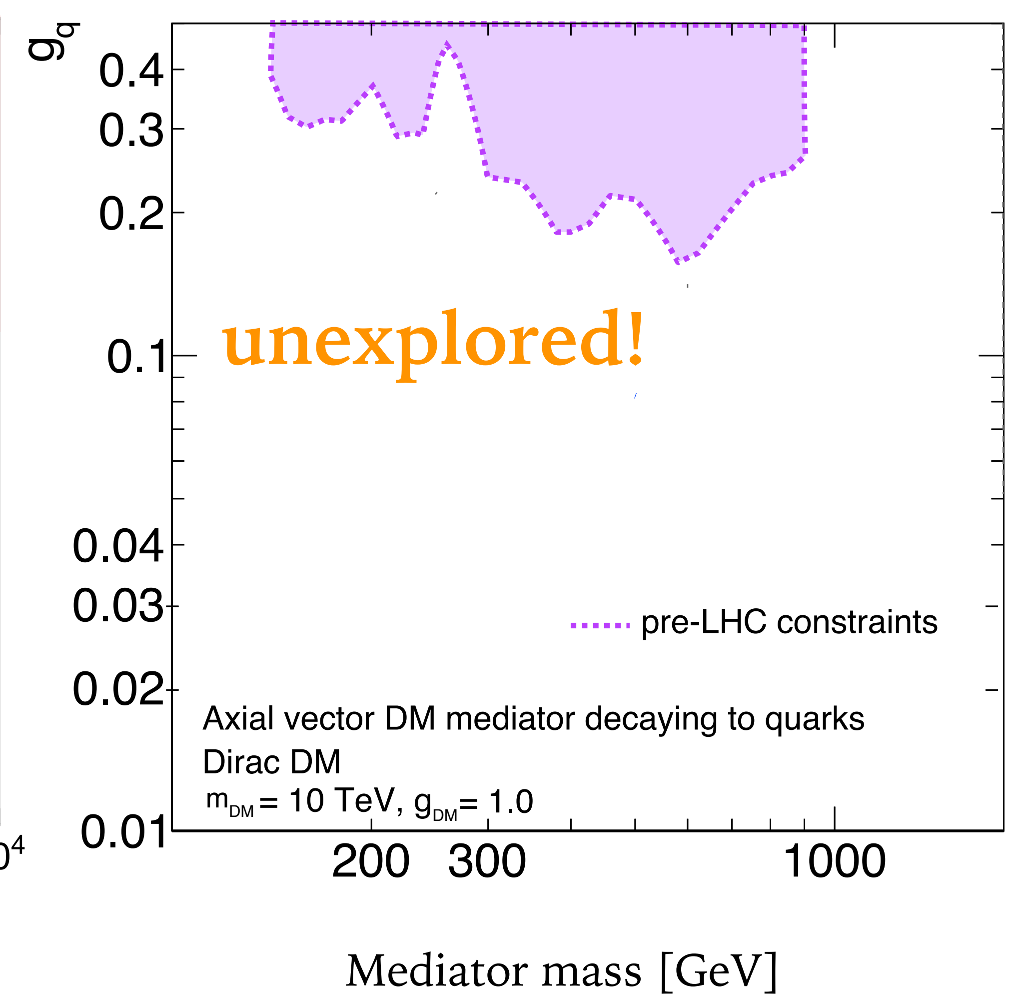
Visible mediator decays



Invisible mediator decays

Adapted from JHEP 1507 (2015) 089





A paradigm change for collider experiments

Asynchronous data analysis

First record and store data, then reconstruct/analyze it

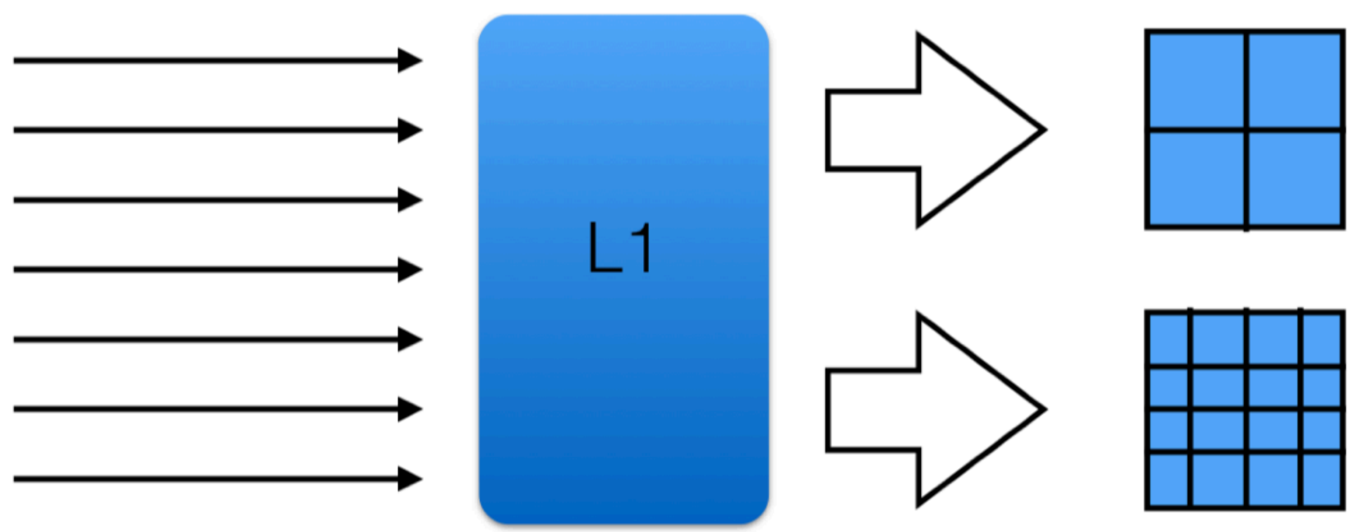
Real-time data analysis

Reconstruct/analyse data as soon as it is read out so that only (**smaller**) final-state information needs to be stored

ATLAS: Trigger Level Analysis **CMS**: [Data Scouting], **LHCb**: [Turbo stream]

(Near-)real-time analysis of LHC data

Enormous amount of data read in at L1 trigger level



Graphics by K. Pachal

Can either store large amount of data for a small number of events....

... or small amount of data for many, many events

Fixed amount of bandwidth

Perform as much "analysis" as possible in real time

- Reconstruction & calibration
- First preselection to skim "backgrounds"

Reduced data formats:

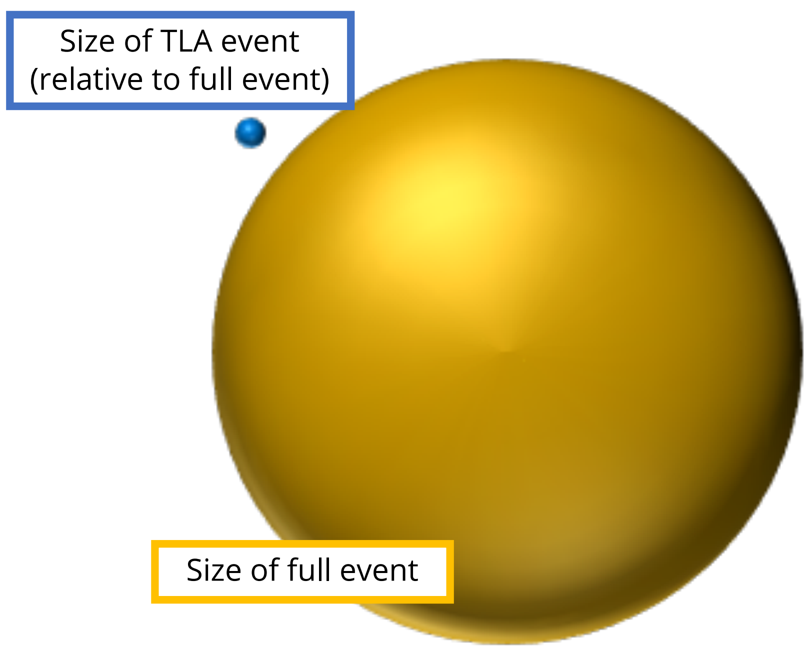
- Only keep final trigger objects (drop raw data)
- Save only "interesting" parts of the detector
- Run-3 / LHCb: A combination of the two

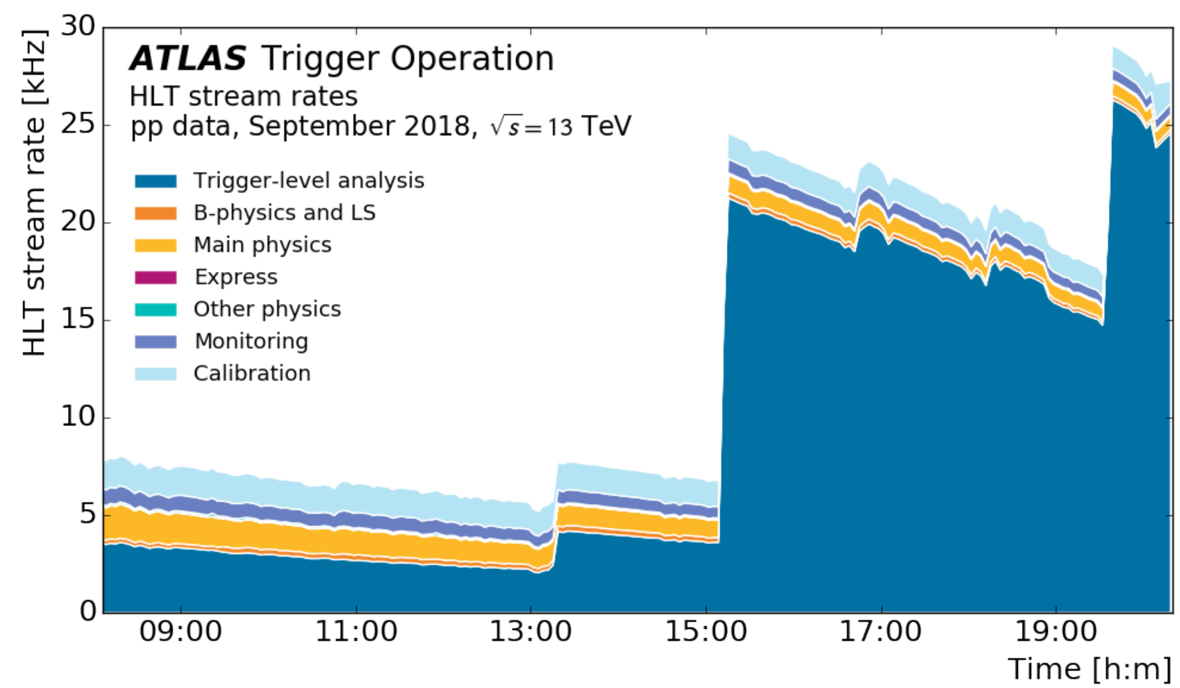
ATLAS implementation: Trigger Level Analysis (TLA) *

Much smaller event size → orders of magnitude more data can be recorded

Data taking
↓
Trigger-level events (reconstructed jets only)
↓
Rejection of most events by the trigger
↓
Full events (includes raw data)
↓
Search for new physics

(Trigger-level events → Search for new physics)



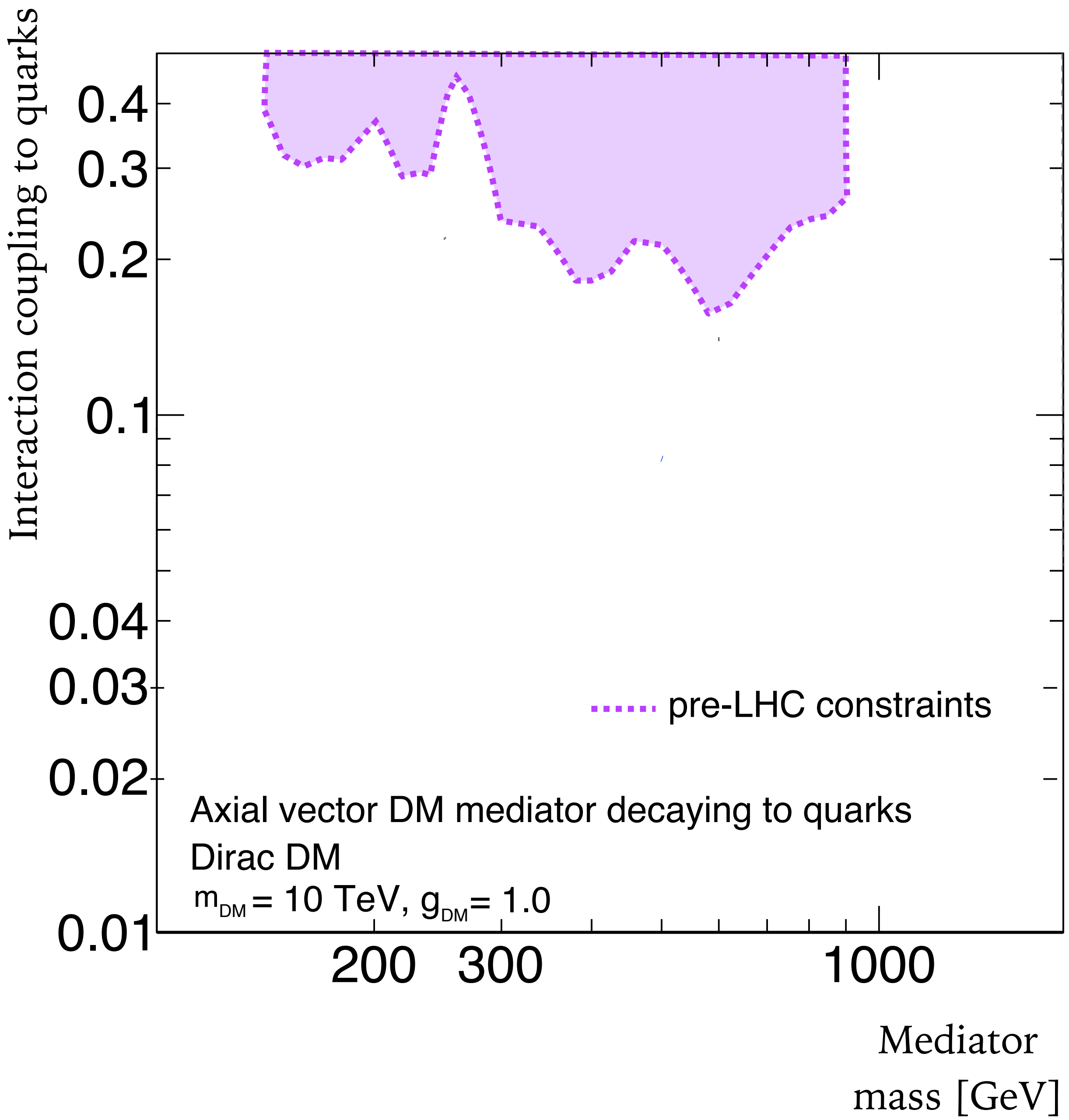


https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TriggerOperationPublicResults

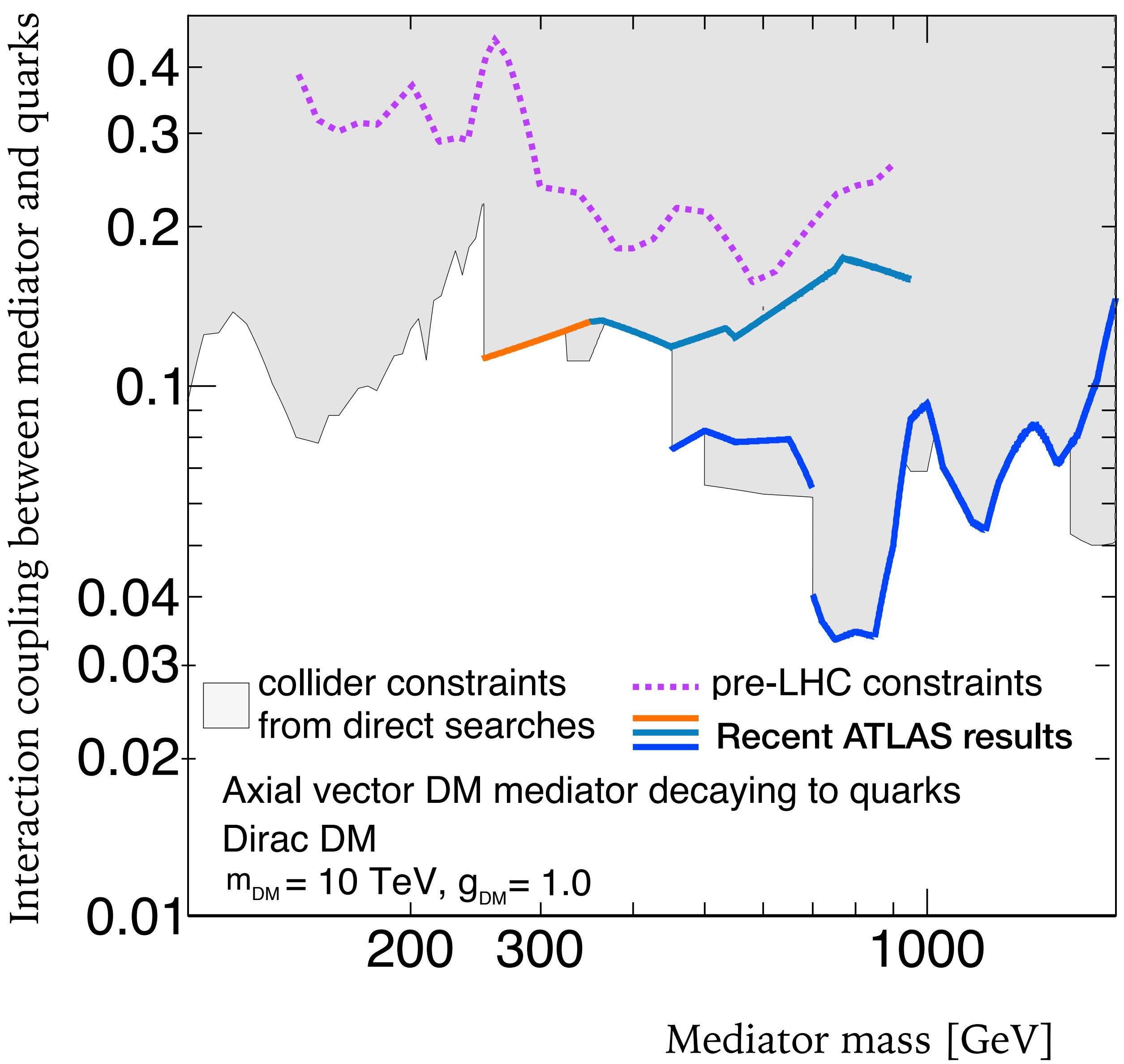
More data → increased sensitivity to rarer processes at lower masses

* Trigger Level Analysis is a Three Letter Algorithm (TLA)

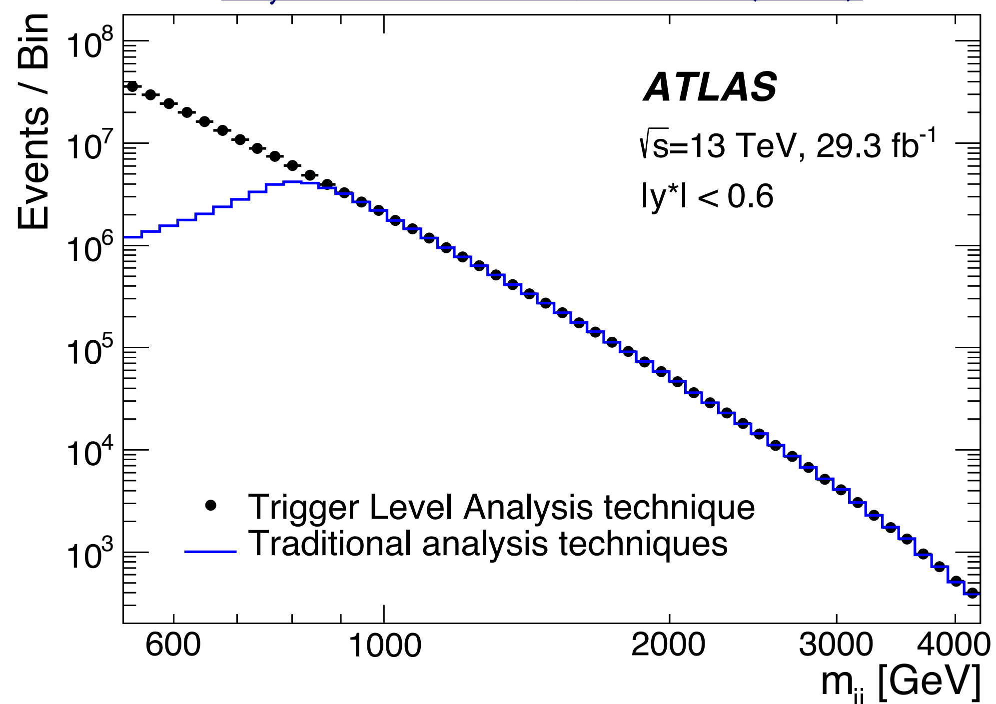
Filling the uncovered parameter space of low-mass



Filling the uncovered parameter space of low-mass

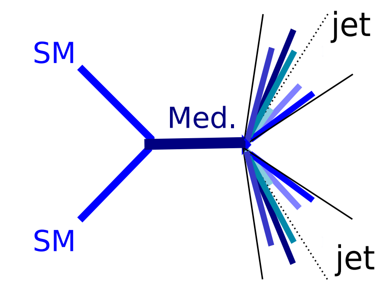


Phys. Rev. Lett. 121, 081801 (2018)

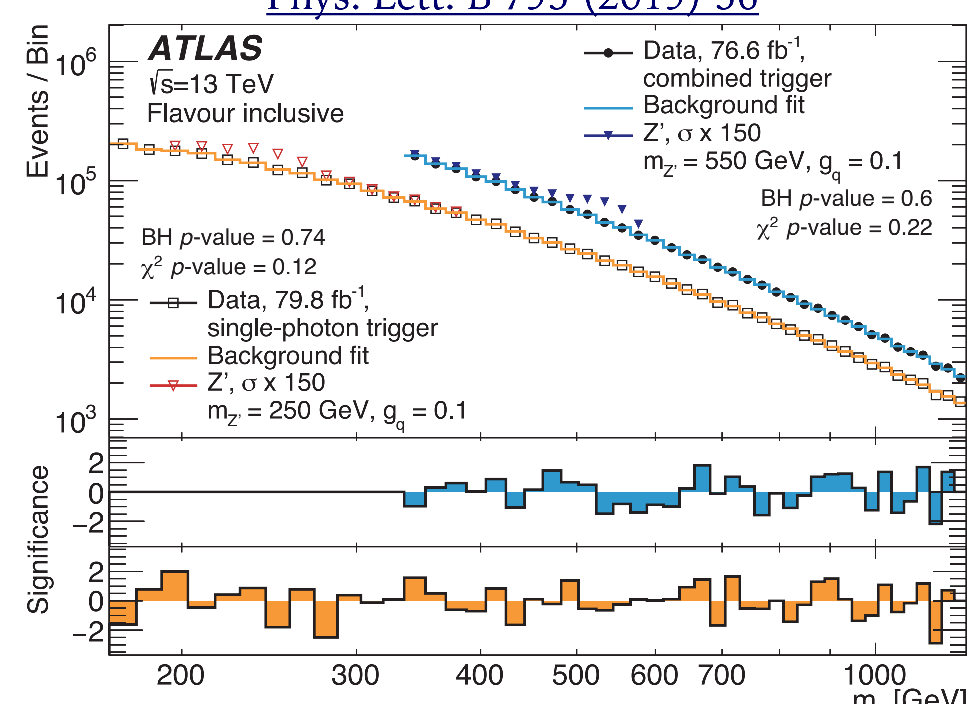


TLA technique:

Make the event size smaller

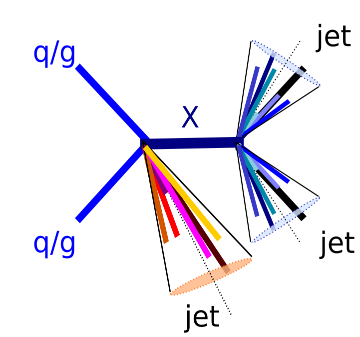


Phys. Lett. B 795 (2019) 56



Dijet+ISR signature:

Reduce the background



UChicago-inspired: Phys.Dark Univ. 2 (2013) 50-57

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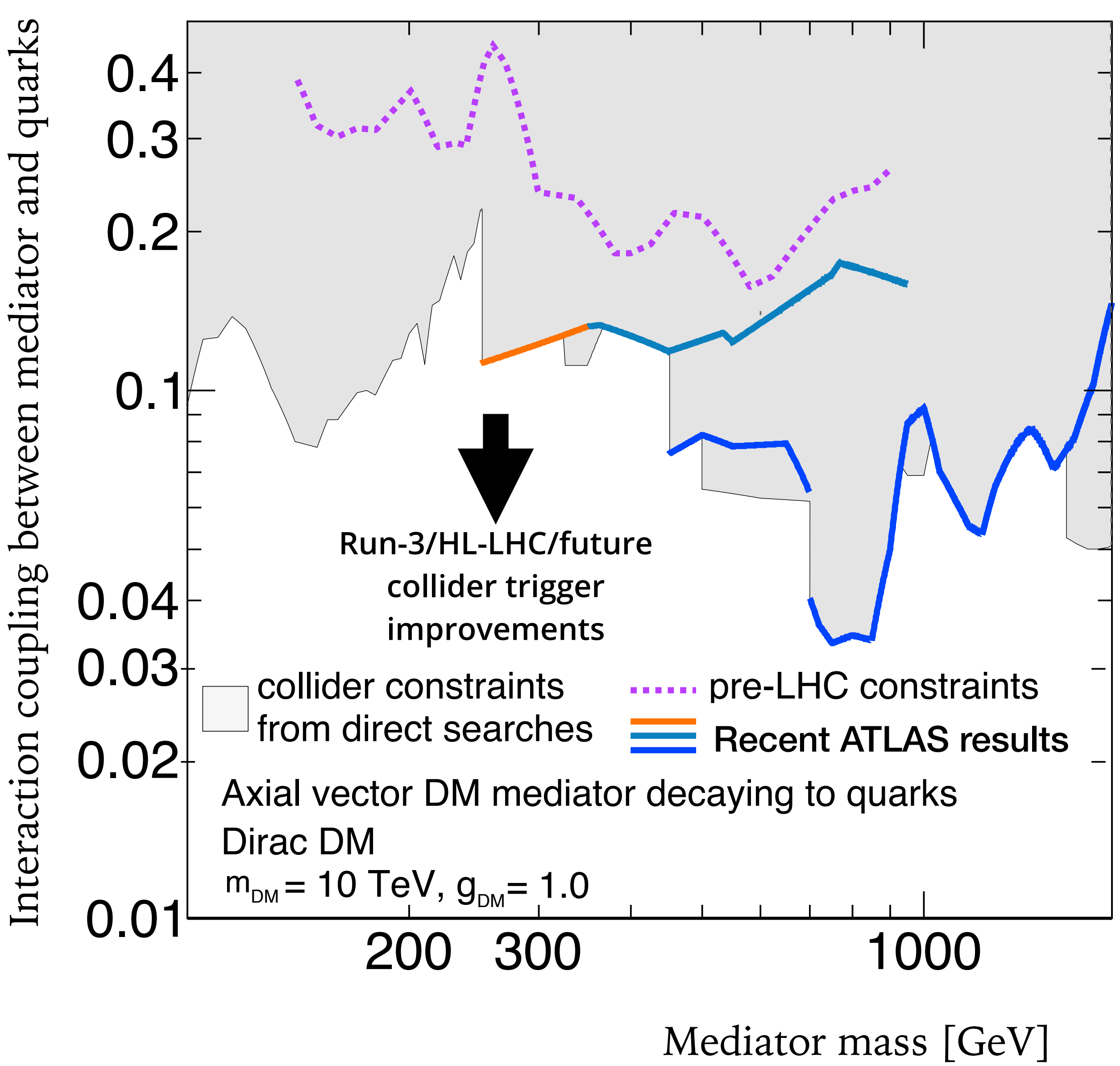
Filling the uncovered parameter space of low-mass



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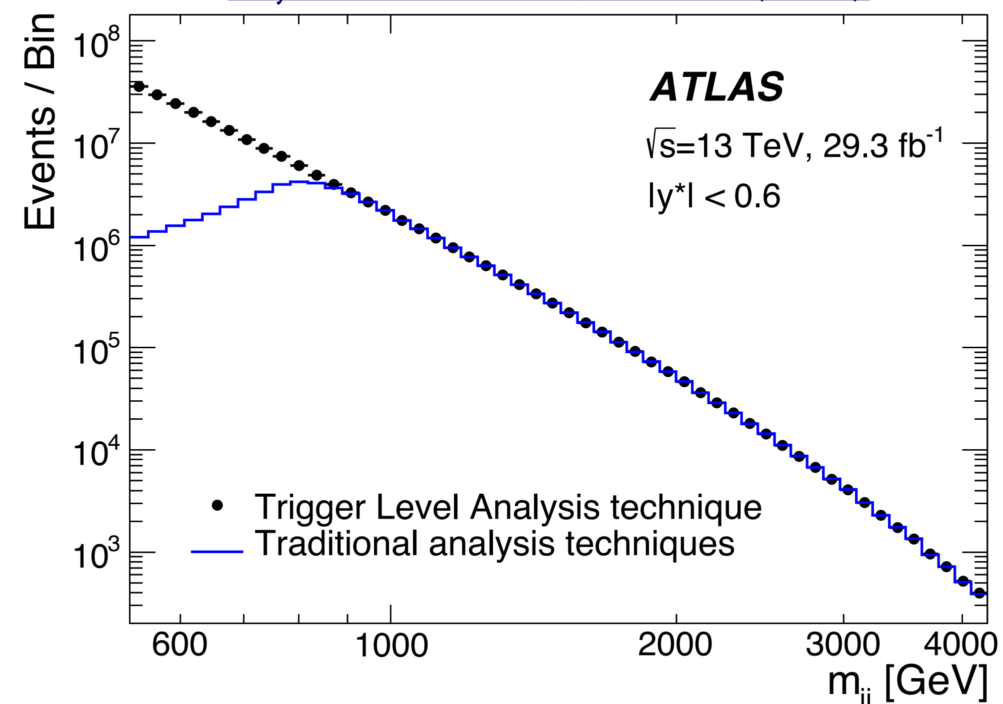

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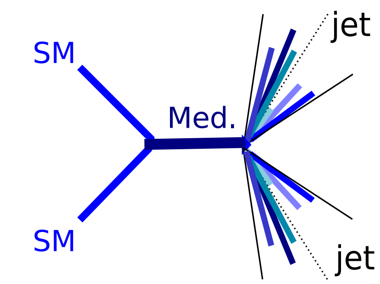

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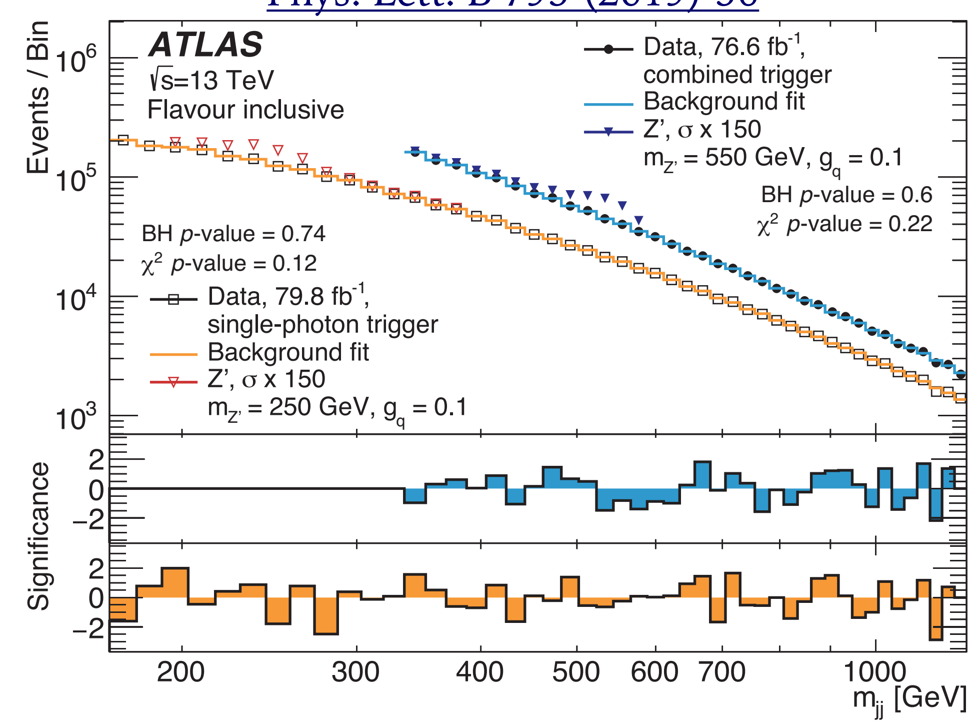
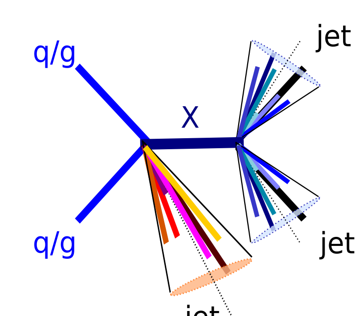


Dijet+ISR signature: Reduce the background



Searching for even rarer dijet resonances: **EW-scale couplings still unexplored** and probably not something we want to give up at any future colliders *(to discuss!)*

You may have noticed:
definitions of *low-mass*/*light* varies...

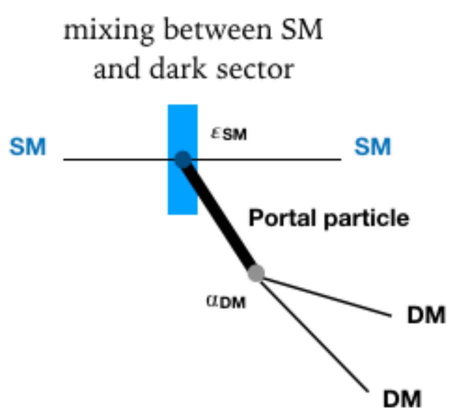
Low-mass mediators to a collider physicist in dijet searches: EW scale [o(100) GeV]

But this mediator can easily *(?)* be connected to less-explored lighter [o(GeV)] mediators

Note: see this summary talk / this review
for searches where the mediator is feebly coupled and therefore displaced

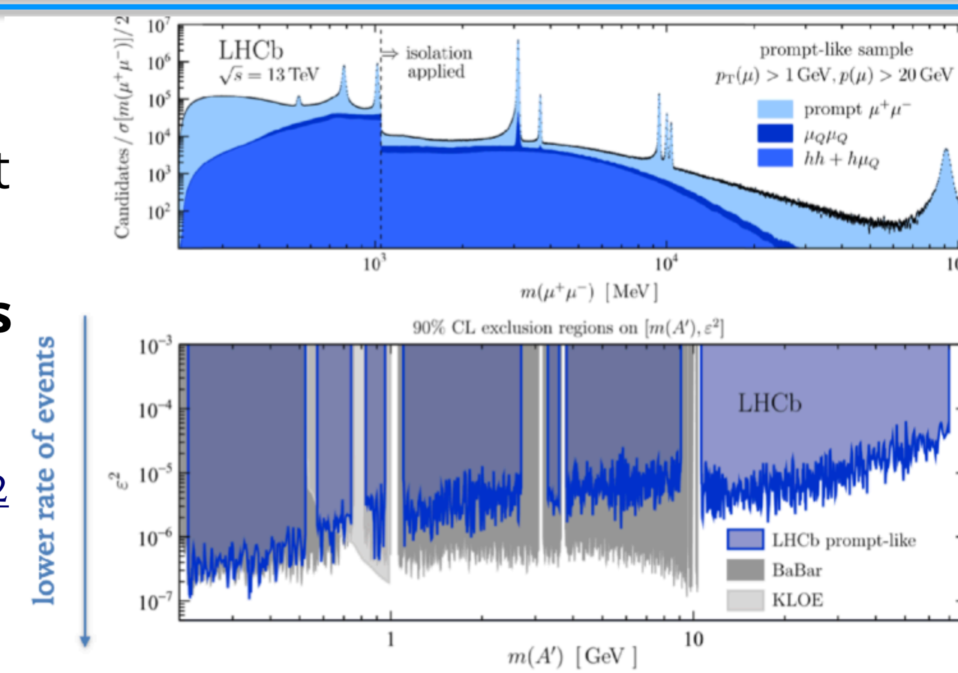
The obligatory dark photon slide

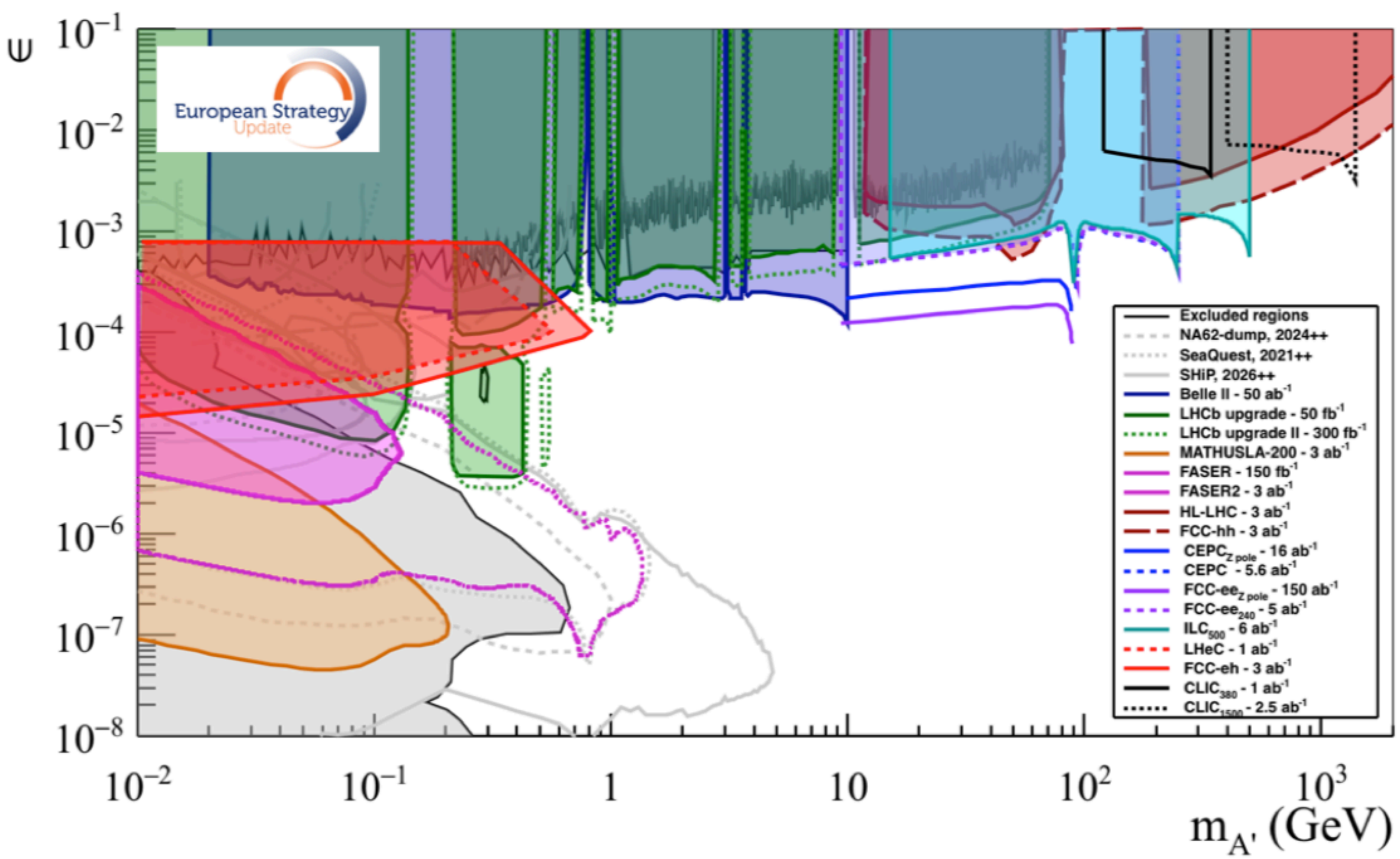
European Strategy Update Briefing Book



Dark photon → *dimuon* searches
face the same problem as dijet searches at masses below the Z
→ **large benefits from real-time analysis (or untriggered colliders)**

Phys. Rev. Lett. 120, 061801 (2018) See also CMS's Phys. Rev. Lett. 124 (2020) 131802

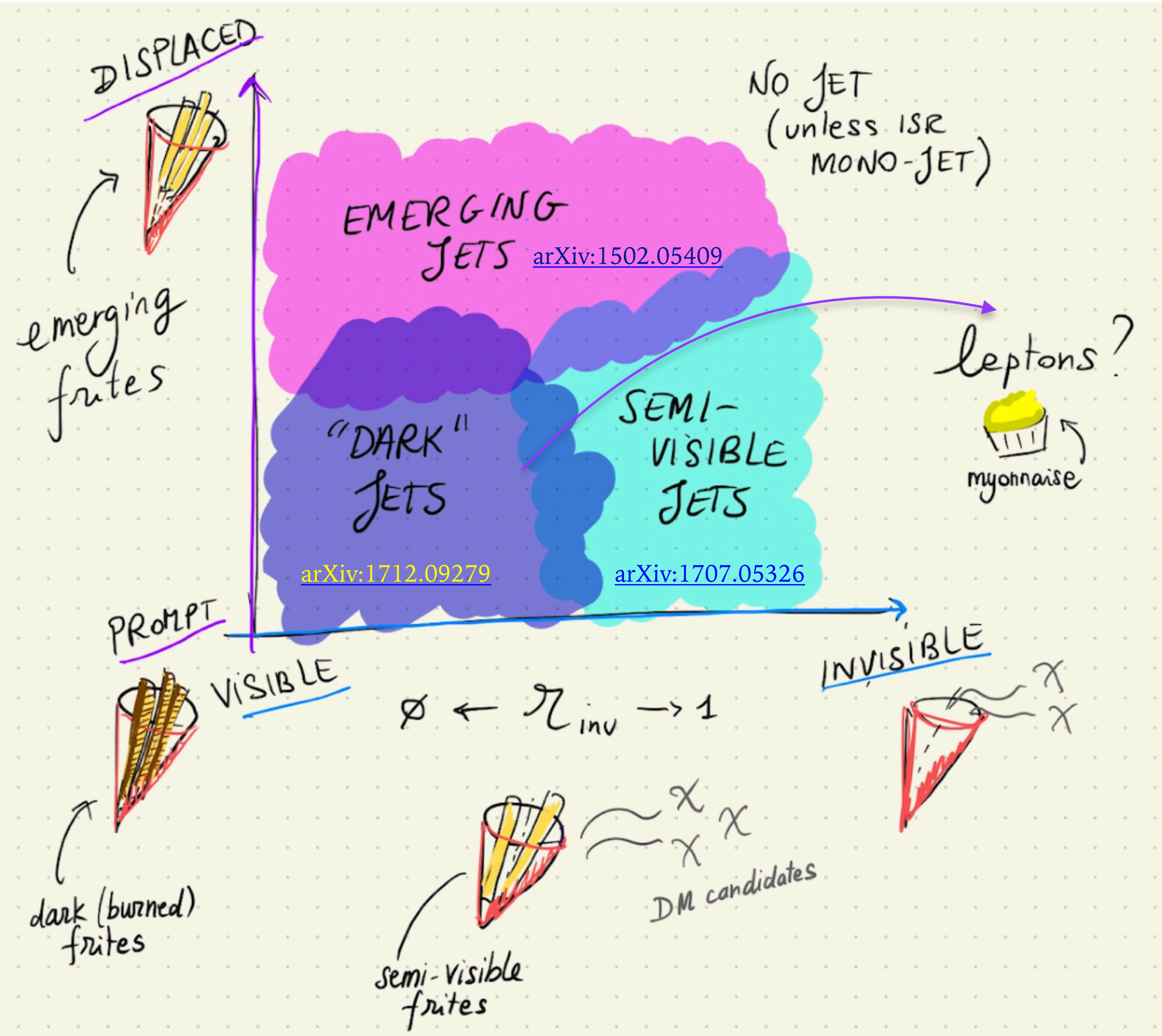




Projections from HL-LHC (and some future colliders) assume trigger thresholds like LHC Run-1

Important to keep in mind non-standard analysis workflows (& work on improving trigger systems) to make the most of future collider data

Strong dark interactions ⇒ non-standard collider jets



Inspired by K. Pedro & C. Fallon's talk @ DMLHC2019 and by this twitter thread

Searches for dijet resonances. ⇒ Nature making our jets weirder than QCD

Going beyond the "low-hanging fruit":

- **Dark sector** models (some including DM candidates) with much uncovered territory
  Class of models including ***dark quarks*** that fragment in a QCD-like way (***dark QCD***):
  - **Dark dijets** → prompt dark sector jet constituents
  - **Emerging jets** → long-lived jet constituents
  - **Semi-visible jets** → invisible jet constituents
- Current searches searching for signals >~ TeV (limited by trigger rates)

SnowMass2021

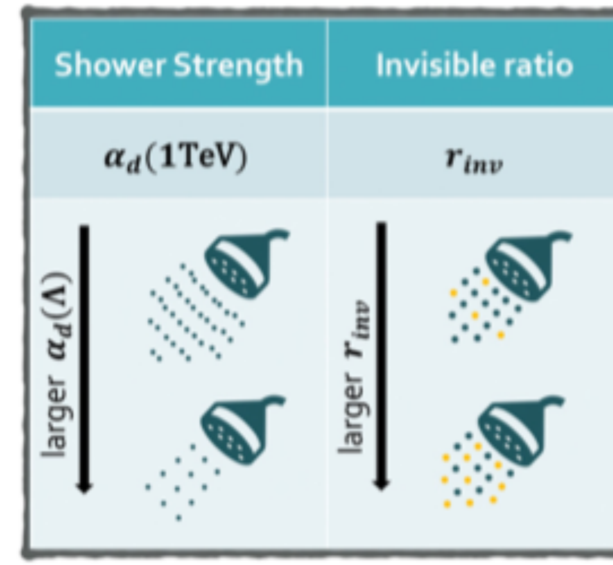
Discussions every ~3 weeks at this indico, hosted by Suchita Kulkarni Marie-Helene Genest

A family of signatures, with DM particles (& more) in the dark shower ⇒ need more than simple real-time analysis!

Can be searched for in LHCb, ATLAS and CMS [arXiv:1810.10069]

Link to data selection: exotic dark jets & other signatures

[Tim Cohen, Snowmass 2021](#)



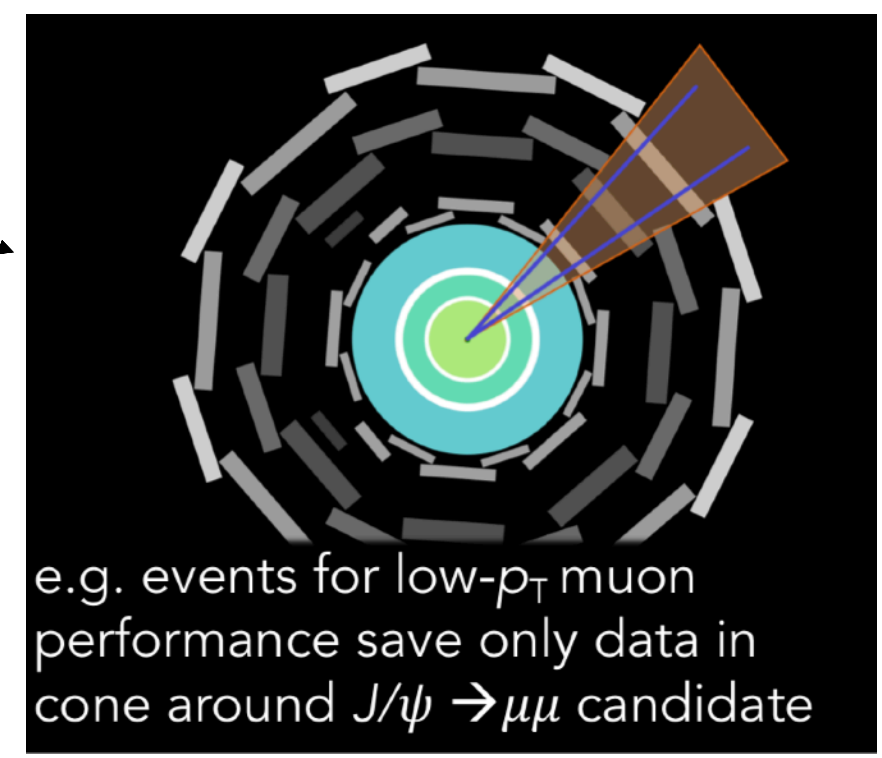
Mapping of "exotic" signatures to big picture of theoretical models not easy
→ difficult to prioritize on theory grounds
→ difficult to decide what exactly to save and select, in advance

Example: group of signatures with a **common denominator**:
unusual tracks/energy distributions,
more or less localized in the detector, e.g. **dark QCD** jets

How do we make sure we don't miss these events?

1. write dedicated trigger algorithms
2. save (custom-reconstructed) trigger-level objects only
3. save a mixture of trigger-level objects and raw data in interesting regions
4. save any of the above and reconstruct data later
5. [outlier detection…in the very far future]

[H. Russell, EPS-HEP 2019](#)



Partial event building

ATLAS/CMS starting a research program, interesting benchmarks for a variety of reasons:

- forces us to understand QCD better
  - Note role of measurements, e.g. CONTUR
- plenty of phase space to be explored
- requires connection between theory, generators, and different experiments (dark sector particles in jets vs 'weird jets' as a whole)

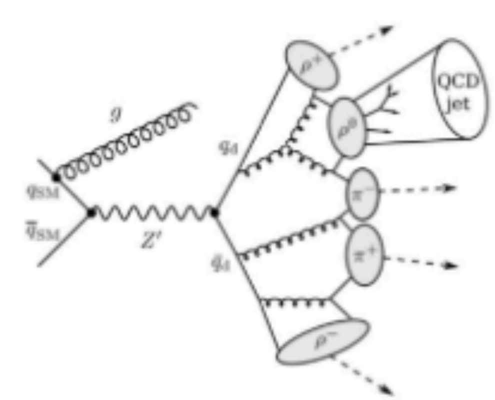
Snowmass 2021: work on dark showers

Dark showers project status and updates

EF10 Focus Topic #2.1: **beyond WIMP**

Dark showers project LOI contacts and organizers: Suchita Kulkarni, Marie-Helene Genest, talk link

arXiv:1907.04346



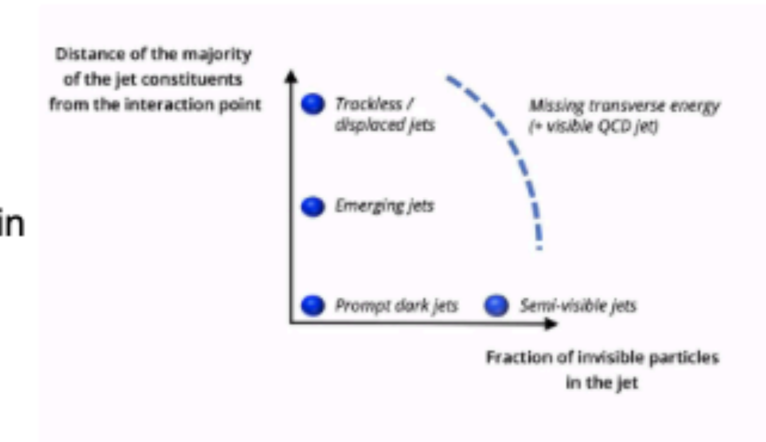
Motivation for dark showers && DM: non-abelian QCD-like theories with dark confinement → dark pions (e.g. one of which can be DM candidate) within dark showers

Challenge: many parameters (details of mediator, details of dark sector…) leading to different signature space

Goals of this working group / common whitepaper:

- Common work on phenomenological studies of existing benchmarks
- Strengthen connections with theory (e.g. meeting on Sept 15th)

Tools: common code and model repository, shared meetings and presentations of different / related LOIs that will lead to different whitepapers within EF09/EF10.



Meetings since 2020: literature survey, connection to broader community (e.g. participation in LLP WG joint sessions including discussions about astrophysics), well-attended tutorials.

Ongoing project example: how the distributions in the colliders vary depending on the parameters of the model (e.g. mediator mechanics).

Message for final whitepaper: pointers to interesting signatures of models containing DM candidates

13

Caterina Doglioni & Liantao Wang - EF10 - 2021/03/09 Snowmass EF Restart Workshop

SnowMass2021

Run-3 prospects in arXiv:1509.06765

See also CMS's Phys. Rev. Lett. 124 (2020) 131802

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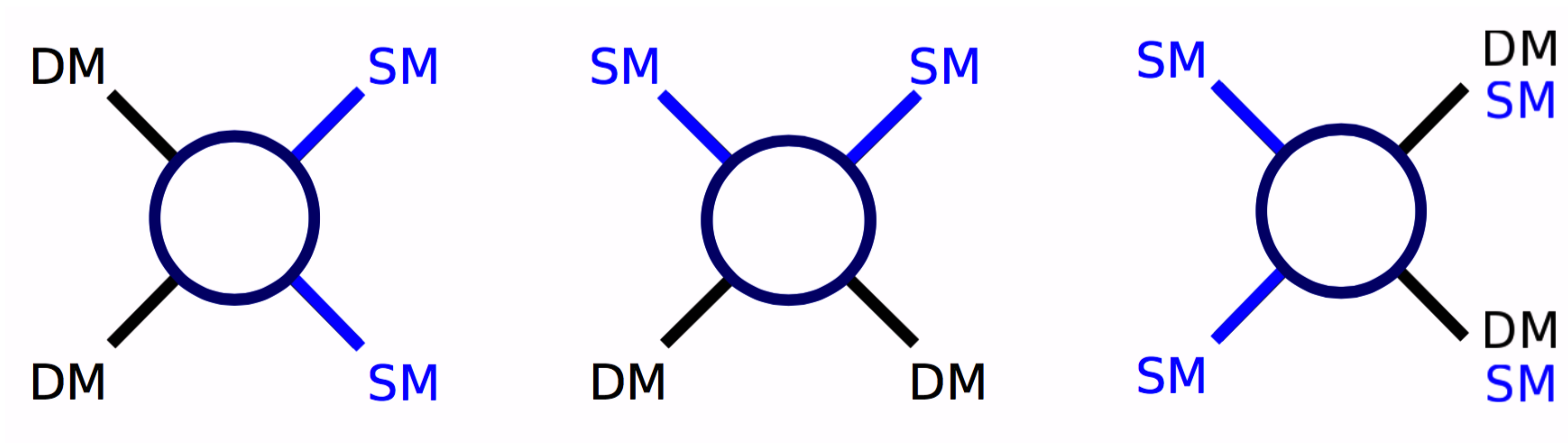
Synergies & complementarity for future BSM searches

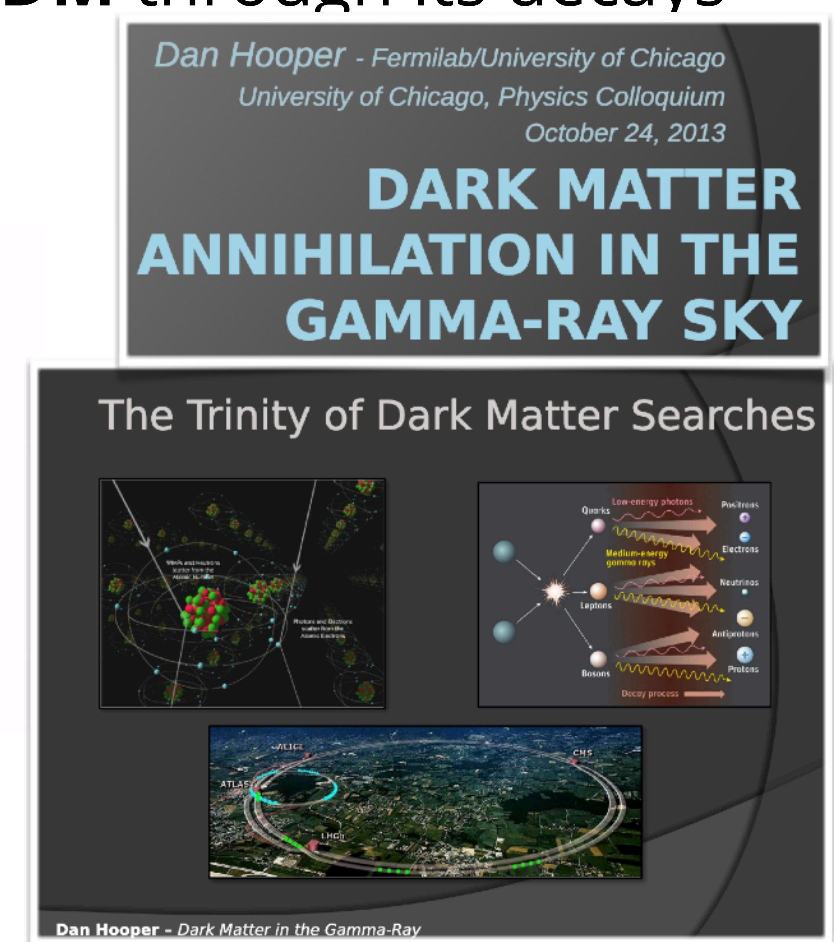
European Research Council
Established by the European Commission

Controversial: why colliders can't discover every/any kind of DM

- **Reason #1**: there are DM models that are not accessible at accelerator energies / intensities
- **Reason #2:** DM discoveries need complementary experiments that involve DM with **cosmological origin**
  - Direct detection can **discover DM that interacts** inside the detector
  - Indirect detection can see **annihilating/decaying DM** through its decays

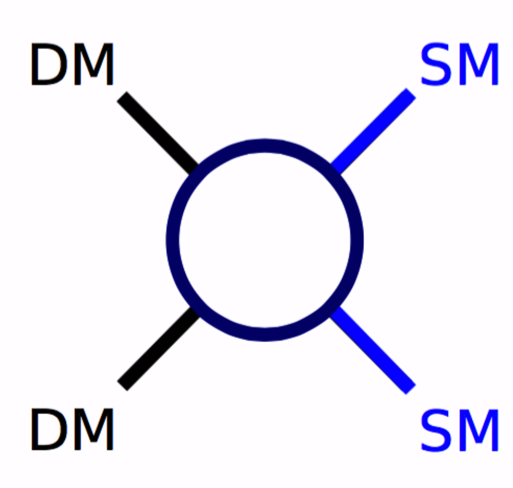


Indirect Detection Direct Detection Colliders

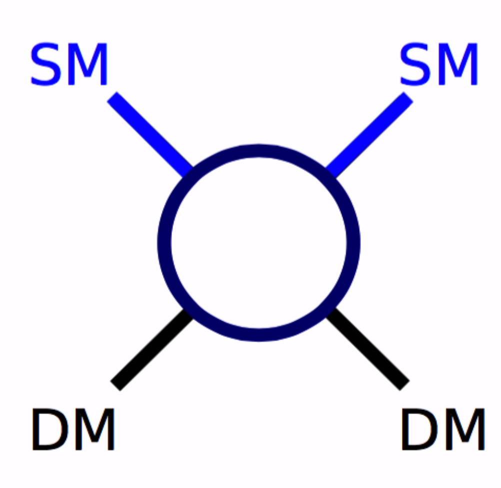


Controversial: why colliders can't discover every/any kind of DM

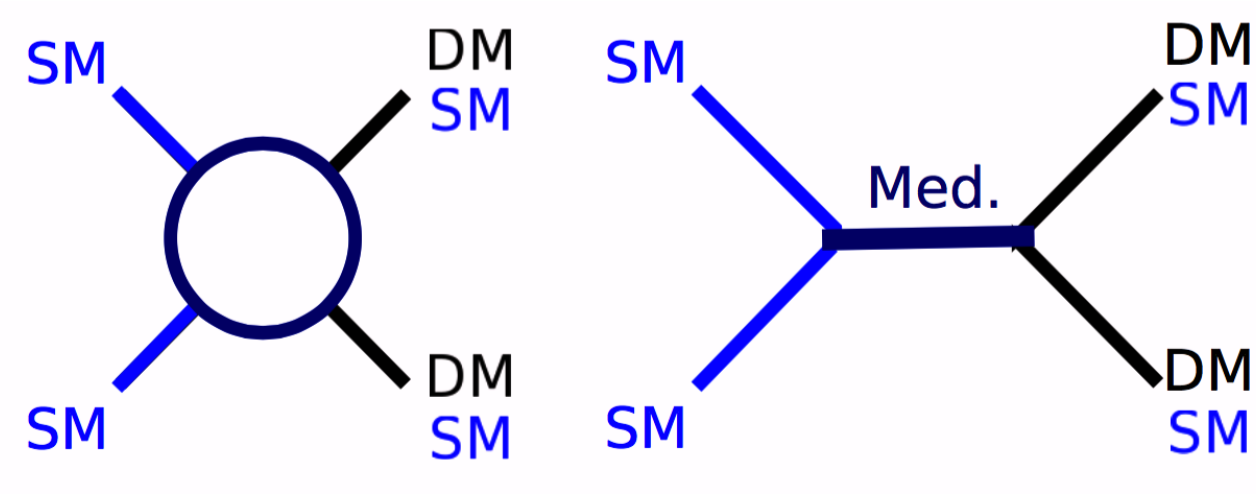
- **Reason #1**: there are DM models that are not accessible at accelerator energies / intensities
- **Reason #2:** DM discoveries need complementary experiments that involve DM with **cosmological origin** / can **produce DM**
  - Direct detection can **discover DM that interacts** inside the detector
  - Indirect detection can see **annihilating/decaying DM** through its decays
  - Accelerators/colliders can produce DM and **probe the dark interaction**



Indirect Detection



Direct Detection



Particle Accelerators (colliders & extracted beam lines)

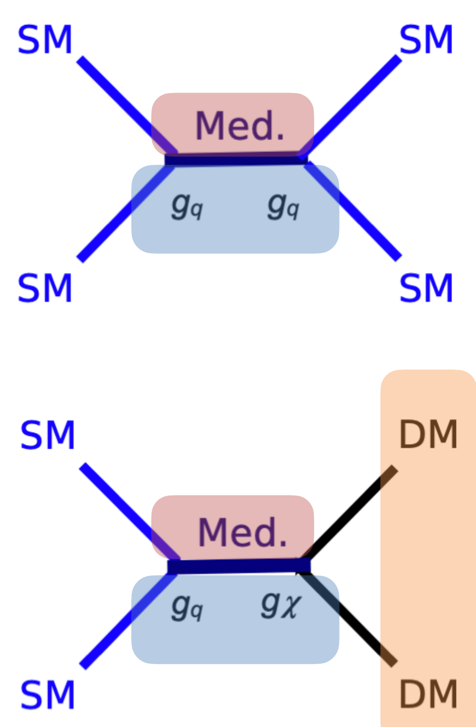
A “global” view of WIMP dark matter

How do we compare results of different experiments ~~in the most model independent way possible?~~

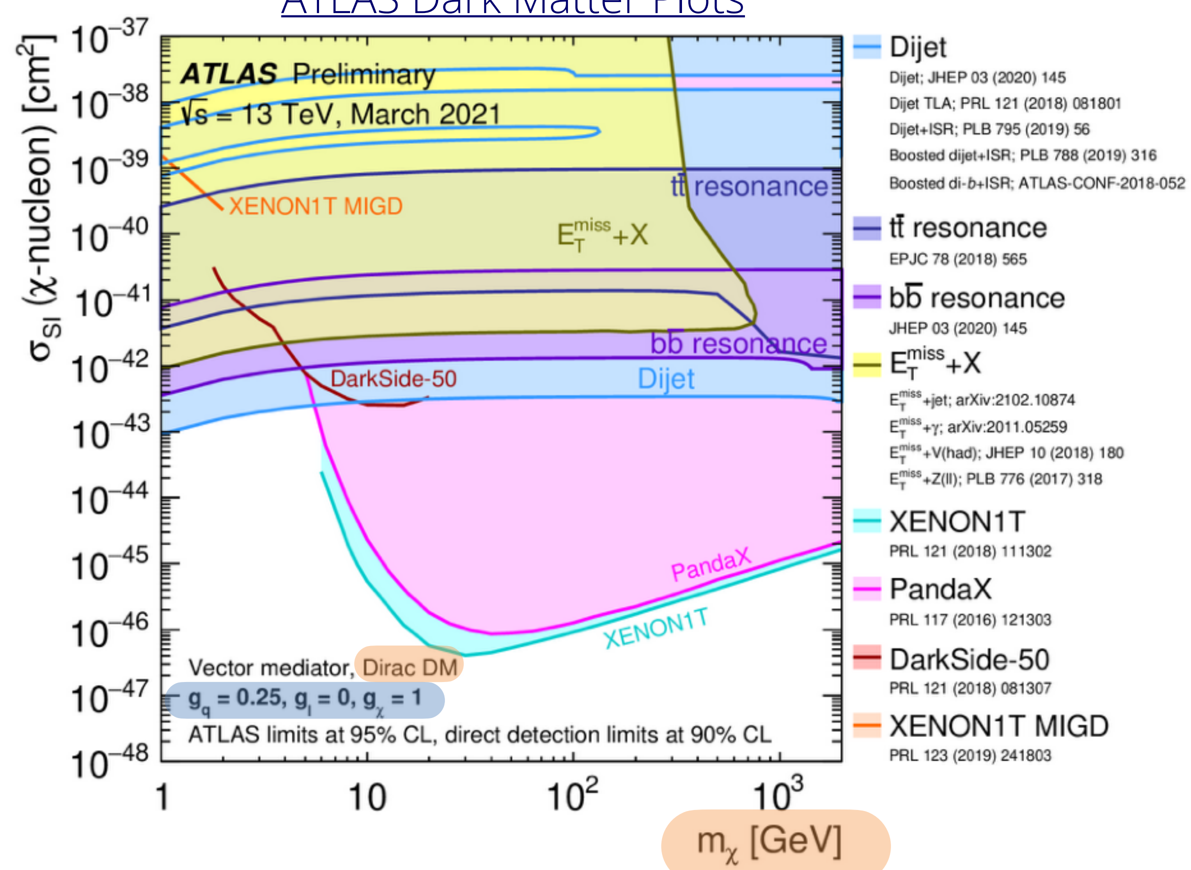
European Strategy Update “Big Question”

Comparisons are possible only in the context of a model
Essential to **fully specify model/parameters** and **be aware of limitations**

LHC Dark Matter Working Group
Phys. Dark Univ. 27, 100365 (2020)



ATLAS Dark Matter Plots

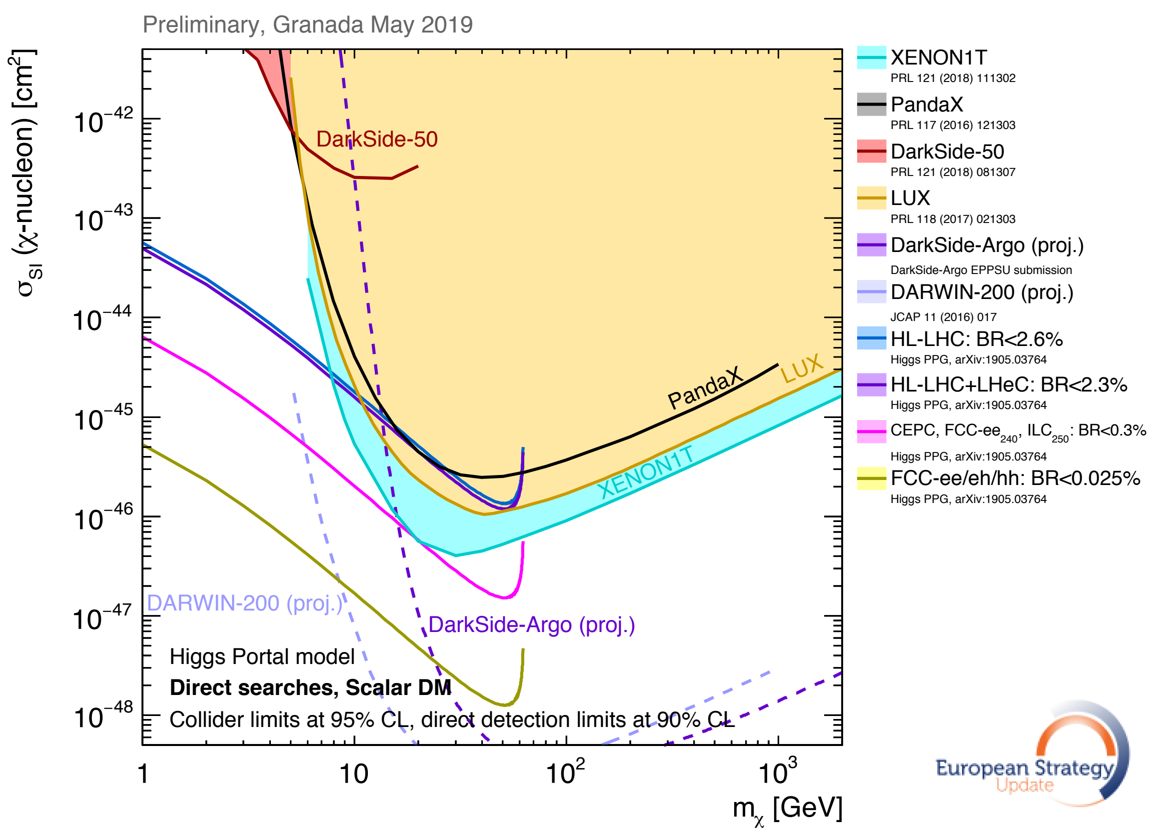


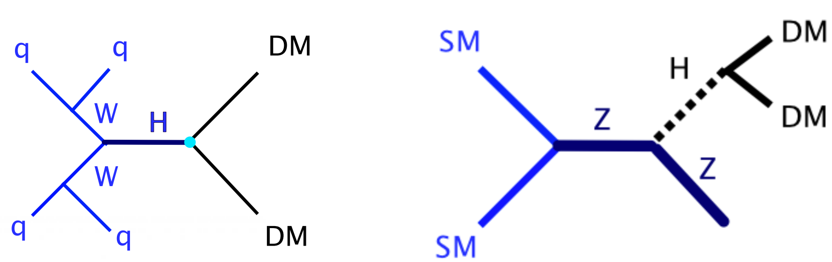
Complementarity of colliders with direct (indirect) detection performed **within the chosen benchmark models & parameters**

Complementarity so far: within WIMP frameworks

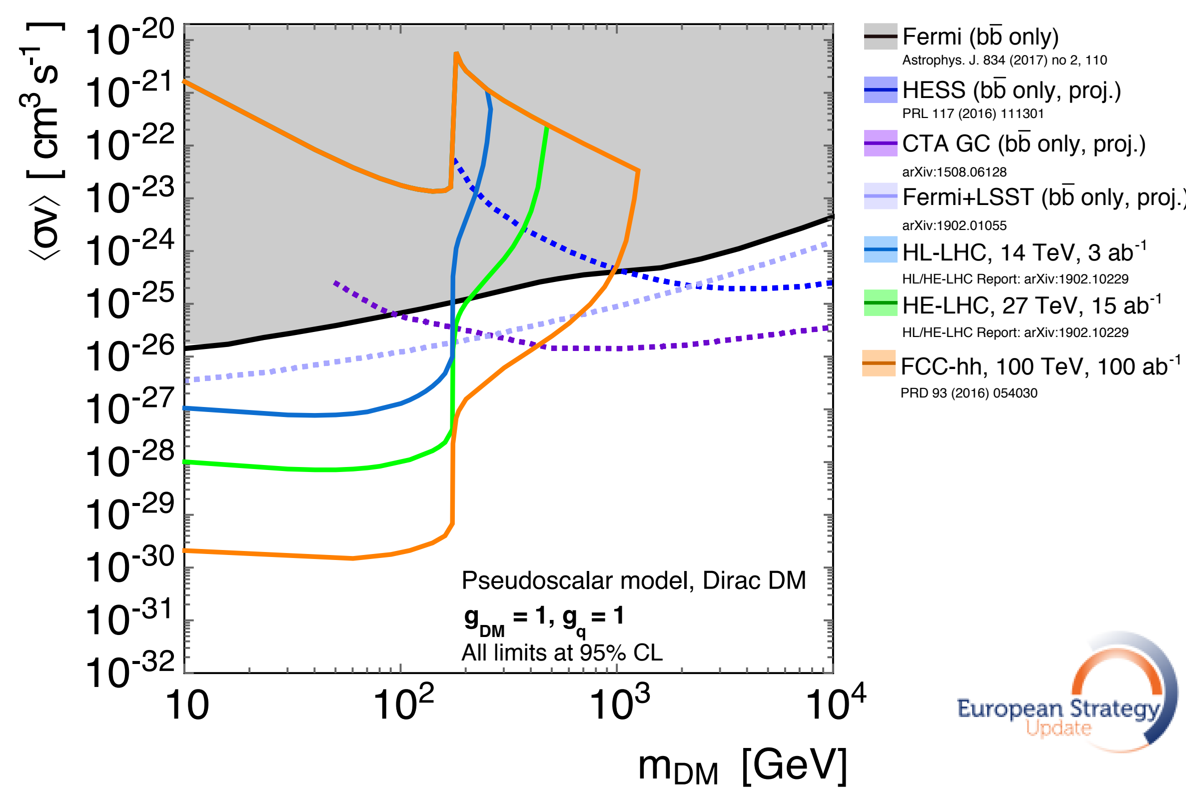
LHC DM Working Group, European Strategy Update Briefing Book, for non-WIMP examples, see Physics Beyond Colliders report

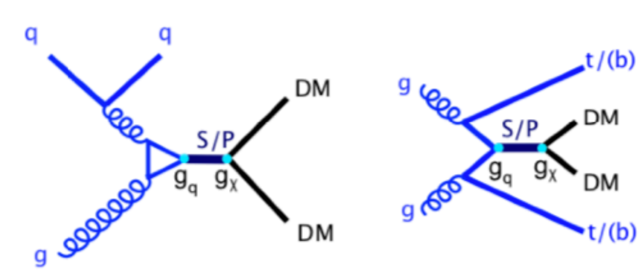
Higgs boson as mediator: colliders & direct detection





Generic scalar mediator: colliders & indirect detection





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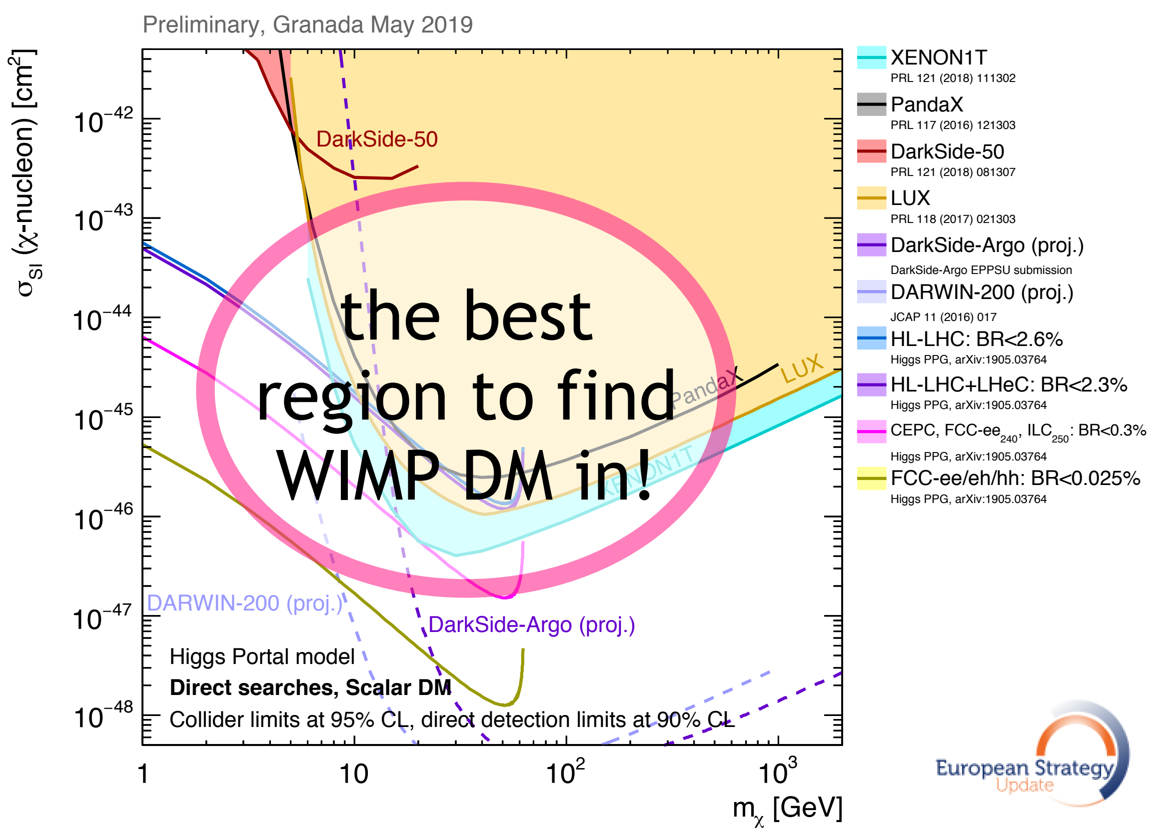
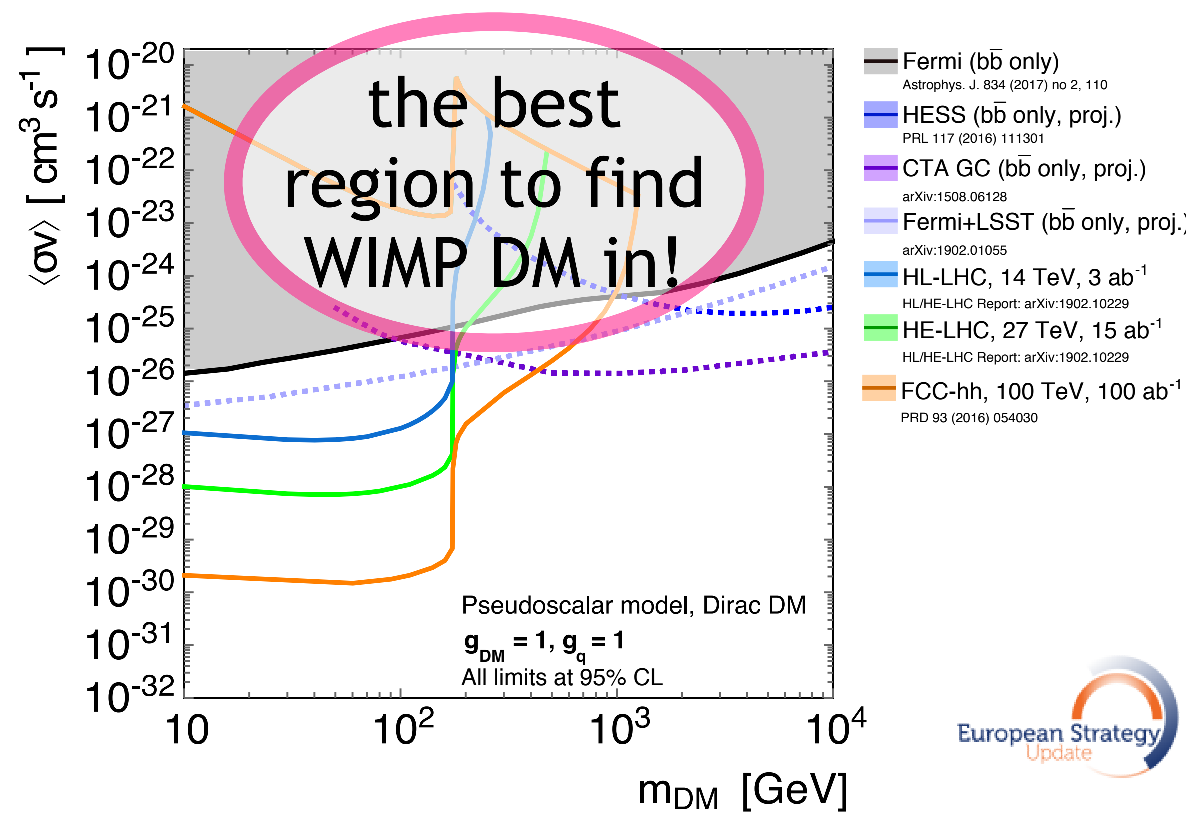
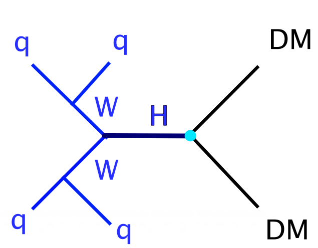
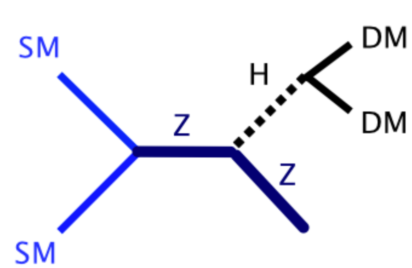


Generic scalar mediator: colliders & indirect detection







Health hazard : these plots are only valid for the couplings specified, in the **limited space of a benchmark model**!
Not to be used to deduce general things like:
"In the next 50 years we will exclude WIMP DM"
"Technique A is better than technique B to find DM"

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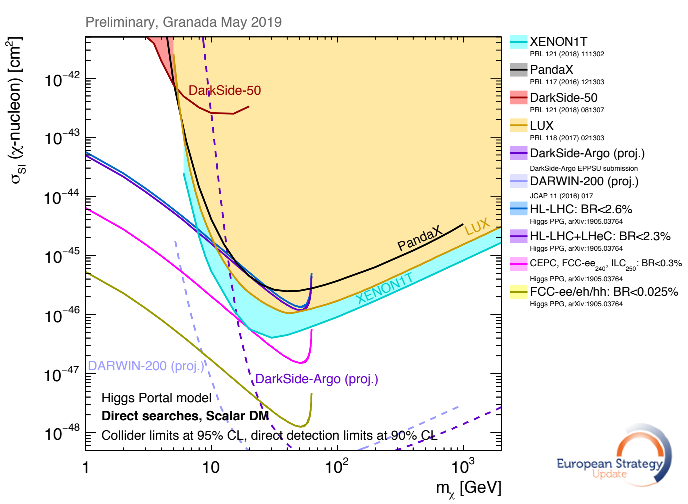
Ongoing work: extending early LHC benchmarks to lower masses /

Can LHC invisible particle searches be interpreted in terms of arbitrarily low DM masses (/couplings)?

- In principle one ***could*** extend those plots to **m_{DM} < 1 GeV**

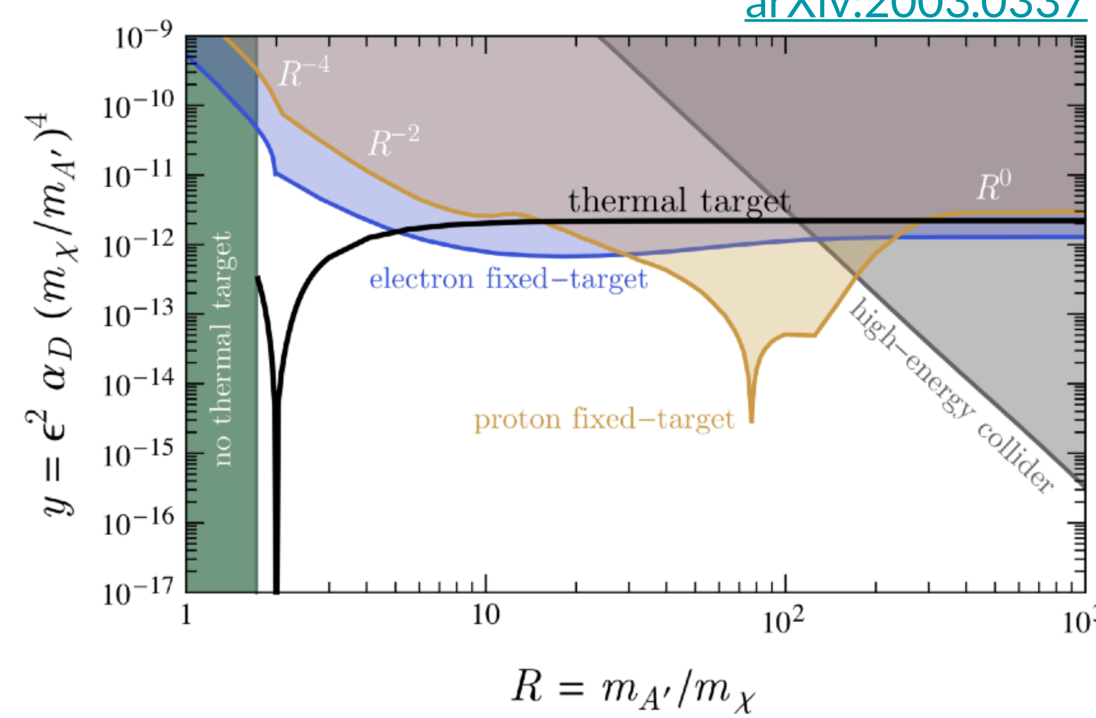


- Are there **theory/nuclear physics issues** in the translation of results?

- Personal feeling (from a collider person!) is that **couplings of order 1 may paint a misleading picture** if we do so, even if we have all caveats specified on the plot → lower coupling models neeed

- (Natalia Toro's) Idea for a complementarity plots to be made in Snowmass, linking lower and higher energy scales

arXiv:2003.0337



SnowMass2021

Discussion needed!

Ongoing work: extending DMWG models to lower masses / couplings

How do generic LHC searches "move on" from benchmarks with couplings of order 1?

(which still have a lot of merit as collider benchmarks)

- Technical "issue": production of new simulated signal samples is a big overhead for "small" LHC analyses → inertia from moving on from previous recommendations

- Solution: analytical methods being developed within ATLAS/CMS/ Snowmass (K. Pachal, A. Albert, B. Gao, E. Corrigan) - Letter of Intent

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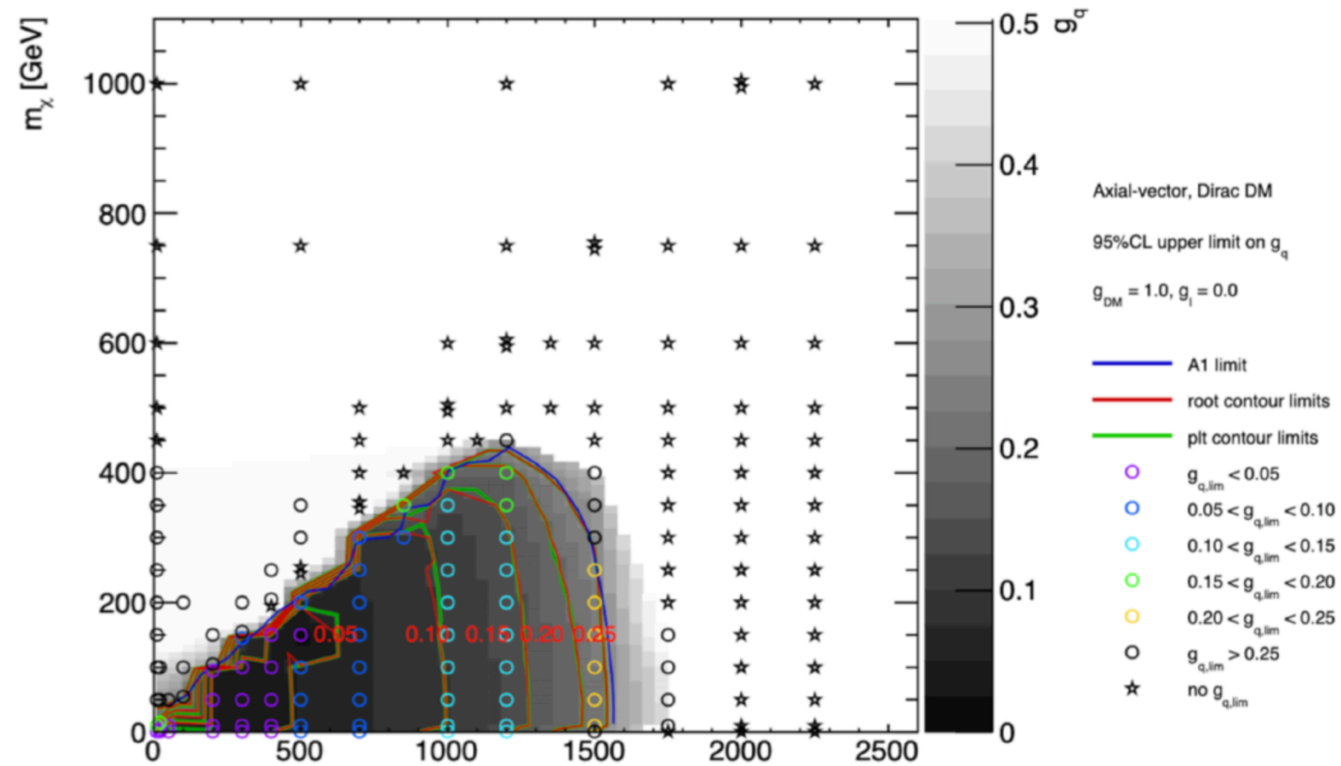
B. Gao's thesis



- Even with analytical methods, filling the low-mDM parameter space requires more samples

- Aim to extend vector/axial vector mediator plots for future colliders with more points at lower mediator/DM masses

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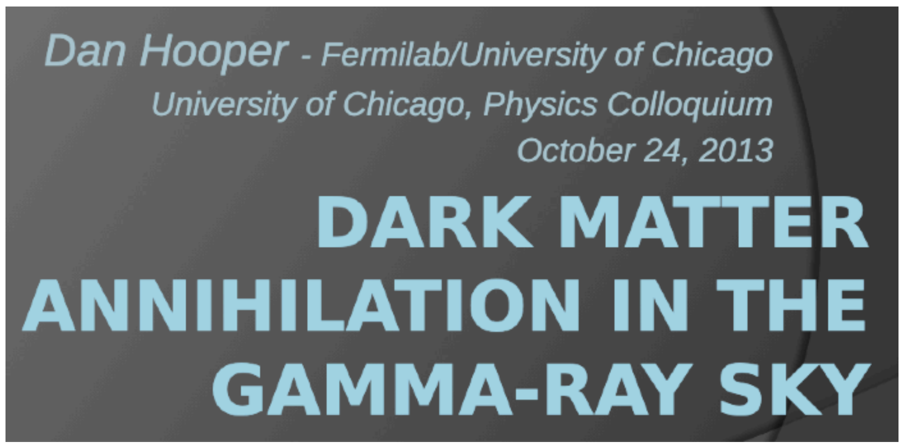
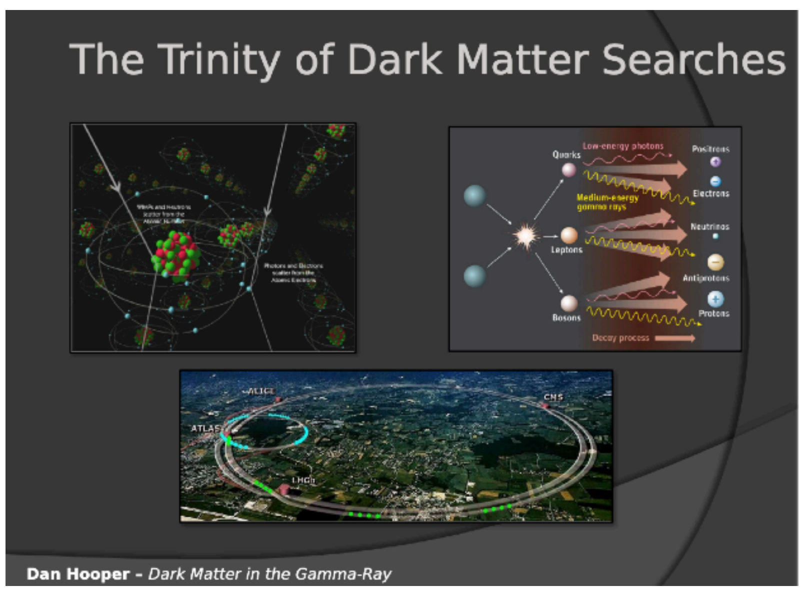
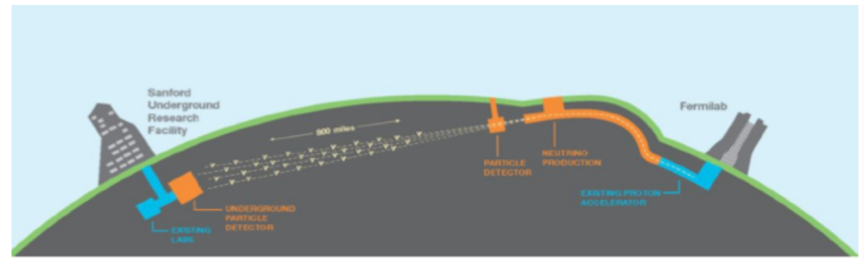
The evolution of dark matter searches in the last decade

Note: not an exhaustive list



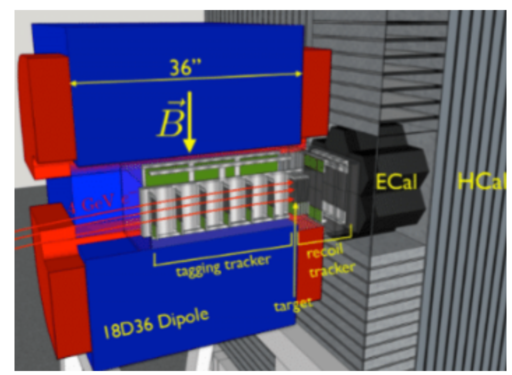


Neutrino experiments



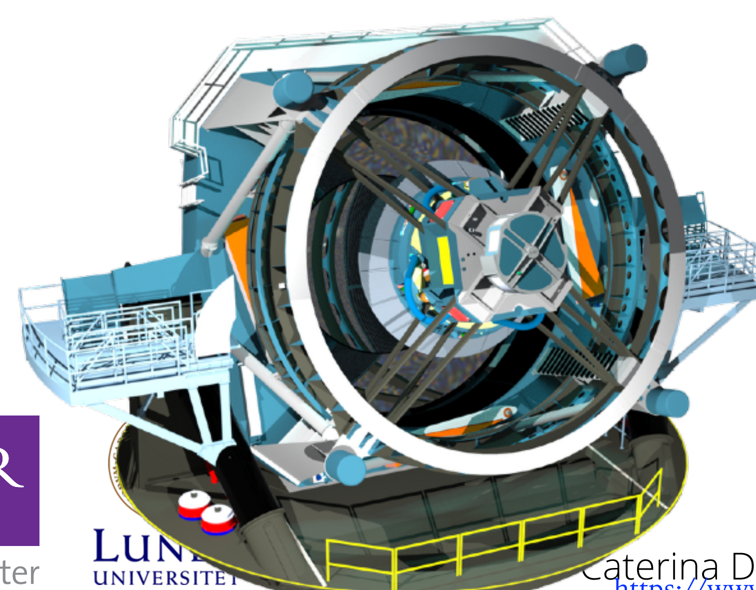
https://www.dunescience.org

Accelerator experiments



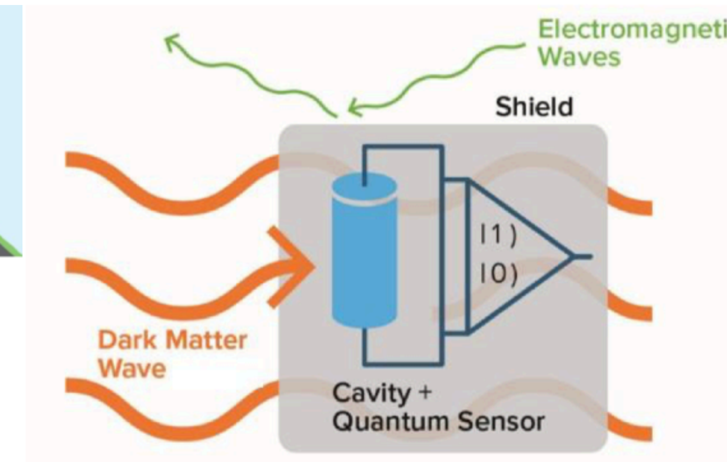
arXiv:1808.05219

Astrophysical probes



https://www.lsst.org

(quantum) sensors for light/ultralight DM



BRN report for new initiatives in DM

Gravitational wave experiments

arXiv:1907.10610

To discuss DM complementarity: SnowMass2021

Link to Community Planning Meeting session #150 - DM complementarity

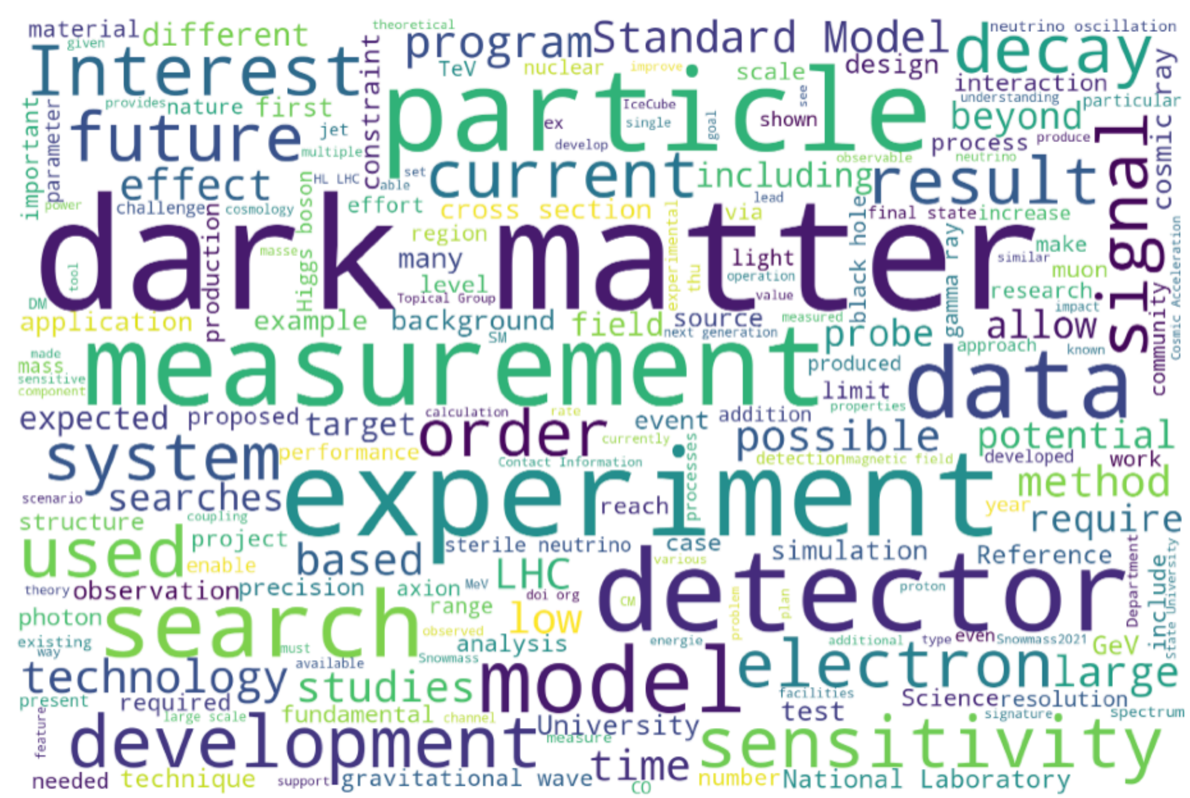
- Since the last Snowmass process (2013), there has been a fundamental shift in how we think about searches for dark matter
- We are in an **exciting exploratory phase** where new ideas can be implemented on short timescales
- Dark matter crosses **every** frontier
- In order to get a full picture of the "elephant", we need to combine information from different experiments
- **How do we portray this complementarity?**
  - You can join us in thinking and making plots (mailing list for when Snowmass restarts: SNOWMASS-DM-COMPLEMENTARITY@FNAL.GOV, instructions on how to join are on snowmass21.org)

https://gordonwatts.github.io/snowmass-loi-words

Word Clouds

Word clouds are made by looking at the word frequency in the LOI's. The more frequent the word, the larger the font-size in the word cloud.

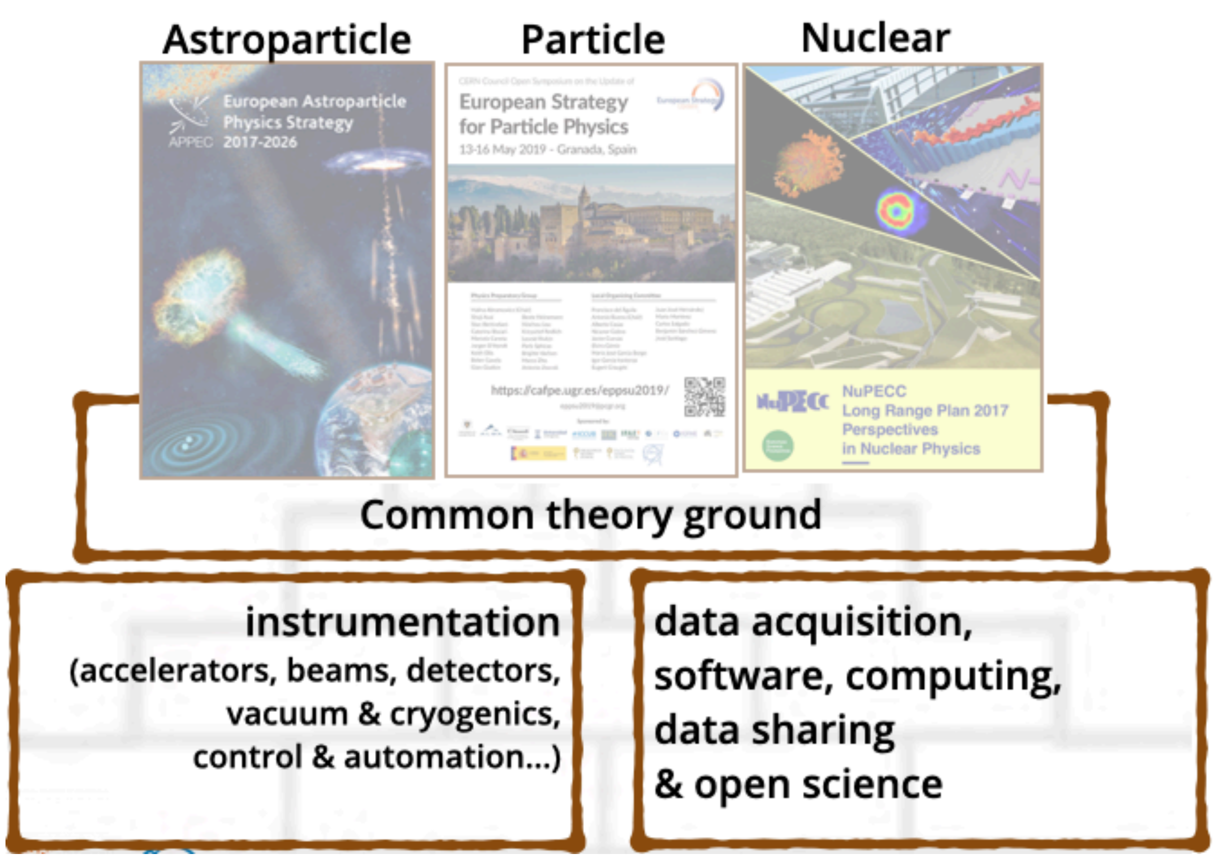
All LOI's



Slide written jointly by Cosmic, Energy and Neutrino Frontier Topical Group Conveners

Two complementary projects (everyone is welcome!)

searches & interpretation



JENAS EoI: Initiative for Dark Matter in Europe and beyond: Towards facilitating communication and result sharing in the Dark Matter community (iDMEu)

https://indico.cern.ch/event/869195/

ESCAPE newsletter APPEC newsletter

build a discussion platform and tools to facilitate collaboration of existing groups/ efforts on **dark matter searches** and their **interpretation**

kick-off meeting 9-12/05/2020

software & data

Towards a Dark Matter Test Science Project

ESCAPE Progress Meeting, 2020

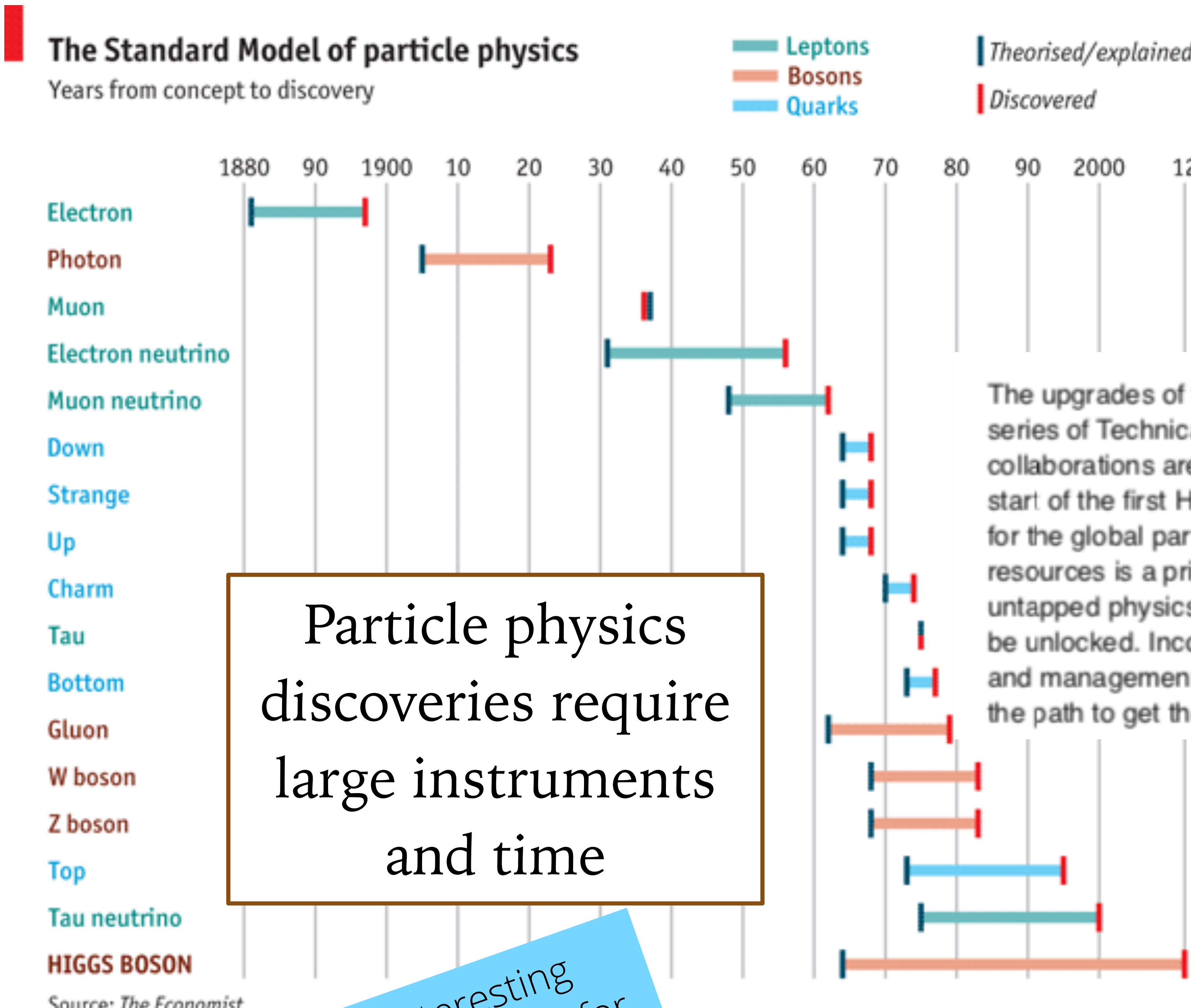
TOOLS conference contribution

compare **end-to-end analysis workflows** for WIMP searches, towards their implementation in a common **Software Catalogue** and as input to the design of the **European Open Science Cloud**

Now hiring!

Conclusions

What does it take for a discovery? ~~Real~~ Time



Particle physics discoveries require large instruments and time

Many interesting upgrades planned for HL-LHC (and beyond)!

[The Economist]

- **We aren't done taking LHC data (10x more expected)** "low-hanging fruit" checked first, expect surprises

[European Strategy Update, deliberation document]

The upgrades of the ATLAS and CMS experiments have been documented in a series of Technical Design Reports and have been approved, and the international collaborations are gearing up to commission these detectors by 2027, the scheduled start of the first HL-LHC run. The timely delivery of these upgrades is a milestone for the global particle physics community, and the continued allocation of adequate resources is a priority. Based on continued innovations in experimental techniques, the untapped physics that is surely awaiting in the third LHC run and the HL-LHC era can be unlocked. Incorporating emerging new technologies into trigger systems, computing and management of big data, reconstruction algorithms and analysis methods is the path to get the best out of these upcoming datasets.

- **Real-time analysis and decision making** cross fields: let's think together and collaborate on tools & infrastructure

What does it take for a discovery? Collaborations

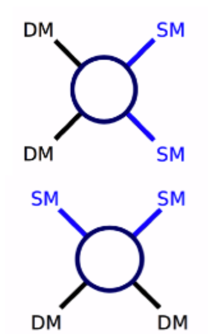
The search for BSM/Dark Matter has a long way to go at future colliders**...**

...it's the perfect time to **search everywhere, including for the rare & unusual**

much larger datasets,
"precision searches"
at colliders and accelerators

new / improved detectors & techniques,
backgrounds & analysis tools

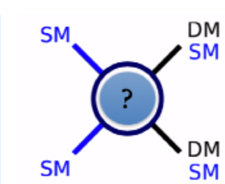
Now and future: essential **complementarity between colliders and other experiments**, *e.g. for dark matter*



cosmological origin
DD/ID/astrophysics

and

nature of the DM-SM interaction
accelerators / colliders



see also Julia Harz's talk on Monday for many more examples

but also on **tools**, given **shared theory, experimental & computing challenges**

SnowMass2021

Towards a Dark Matter Test Science Project

iDMEu
initiative for Dark Matter in Europe and beyond

We can continue the discussions / work together!

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Backup slides

Photo credits: C Fitzpatrick

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CoM energy vs # of Higgs bosons

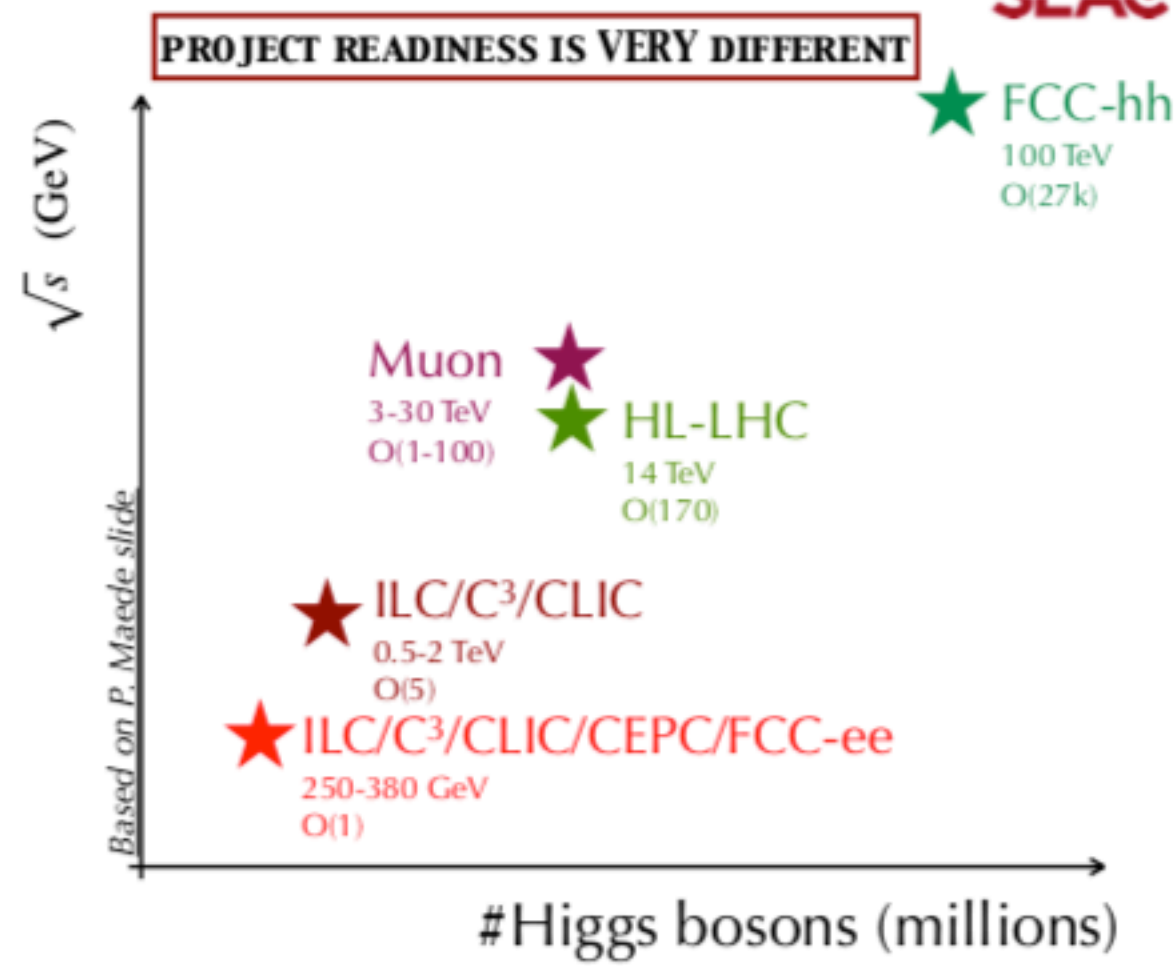
Which collider?

Lepton colliders

- **Circular e+e-** (CEPC, FCC-ee)
  - **90-350 GeV**
  - *strongly limited by synchrotron radiation above 350– 400 GeV*
- **Linear e+e-** (ILC, CLIC, C^3)
  - **250 GeV — 3TeV**
  - *Reach higher energies, and can use polarized beams*
  - *Relatively low radiation / beam induced backgrounds*
  - *C^3 plans is to run at 250/550 GeV*
    C3 proposal - talk on Wed
- μ+μ-
  - **3-30 TeV**

Hadron colliders

- **75-200 TeV** (FCC-hh)



Caterina Vernieri EF Workshop Restart - August 30, 2021 4

A comparison of collider parameters

Emerging Future Colliders

Many Opportunities at the Energy Frontier

FCC-pp	100 km	100 TeV ~ E_{qq}~15 TeV	500 - 3000 $fb^{-1}sy^{-1}$
FCC-ee	100 km	240, 365 GeV	850, 155 $fb^{-1}sy^{-1}$
CLIC-ee	50 km	0.38,1.5, 3 TeV	150, 370, 590 $fb^{-1}sy^{-1}$
ILC-ee	31 km	250, 500 GeV	75, 180 $fb^{-1}sy^{-1}$
C^3-ee	7 km	250, 500 GeV	100, 200 $fb^{-1}sy^{-1}$
HL-LHC	27 km	14 TeV ~ E_{qq}~ 2 TeV	200 - 500 $fb^{-1}y^{-1}$
μCol	27 km	15 TeV	2000 $fb^{-1}sy^{-1}$
μCol	6 km	3, 6 TeV	200, 500 $fb^{-1}sy^{-1}$
μCol	0.3 km	125 GeV	1 $fb^{-1}sy^{-1}$

8-Sep-21 Sridhara Dasu (Wisconsin) snowmass year = 10^7s 4

Fine tuning parameter details

European Strategy Update Briefing Book

Table 8.1: Estimates of the degree of fine tuning in SUSY theories that can be probed with measurements of stop and gluino masses. The fine-tuning parameter is defined as $1/\varepsilon \equiv \Delta m_h^2/m_h^2$ [455], where Δm_h^2 is the contribution to the physical Higgs mass m_h, which for stops (at one-loop) and gluino (at two-loops) is given by $1/\varepsilon_{\tilde{t}} = (3y_t^2 m_{\tilde{t}}^2/2\pi^2 m_h^2)\ln(\Lambda/m_{\tilde{t}})$ and $1/\varepsilon_{\tilde{g}} = (4y_t^2\alpha_s m_{\tilde{g}}^2/\pi^3 m_h^2)\ln^2(\Lambda/m_{\tilde{g}})$ in leading-log approximation. For high-scale SUSY-breaking mediation $\ln(\Lambda/m_{\tilde{t},\tilde{g}}) \approx 30$ is taken, while for low-scale mediation $\ln(\Lambda/m_{\tilde{t},\tilde{g}}) \approx 1$ is used.

ε	High-scale mediation	Low-scale mediation
stop	$5\times10^{-5}\left(\frac{10\text{ TeV}}{m_{\tilde{t}}}\right)^2$	$2\times10^{-3}\left(\frac{10\text{ TeV}}{m_{\tilde{t}}}\right)^2$
gluino	$7\times10^{-6}\left(\frac{17\text{ TeV}}{m_{\tilde{g}}}\right)^2$	$6\times10^{-3}\left(\frac{17\text{ TeV}}{m_{\tilde{g}}}\right)^2$

DM@Colliders work in Snowmass 2021

List of focused questions from Snowmass EF10 (DM @ Colliders)

1. How can we best test the **WIMP** paradigm?
   - Through the simplest/minimal WIMP models (EW multiplets) and their extensions
   - Using simple mediator models (s-channels/t-channels) already used for collider searches
   - Through the Higgs portal, since the Higgs boson is the most relevant portal operator between SM and DM and there are connections to precision measurements

2. How can we best explore **beyond-WIMP** scenarios?
   - Using portals that privilege light dark sectors / dark matter
   - Focusing on less-explored signatures of dark sectors that can highlight present/future blind spots

3. How to best exploit **synergies & complementarity** between DM@colliders & other TGs and Frontiers
   - In terms of different experiments / observations answering the same physics question on the nature of DM
   - In terms of detector, data acquisition and trigger design [e.g. IF04 kick-off]

5

Caterina Doglioni & Liantao Wang - EF10 - 2021/03/09 Snowmass EF Restart Workshop

More about iDMEu

iDMEu

initiative for Dark Matter in Europe and beyond

[iDMEu kick-off - 2021/05/10-12](https://indico.cern.ch/e/iDMEu)
https://indico.cern.ch/e/iDMEu

The JENAA iDMEu LOI proponents:
Elena Cuoco, Jocelyn Rebecca Monroe
Marco Cirelli, Silvia Pascoli
Caterina Doglioni, Federica Petricca
Gaia Lanfranchi, Florian Reindl

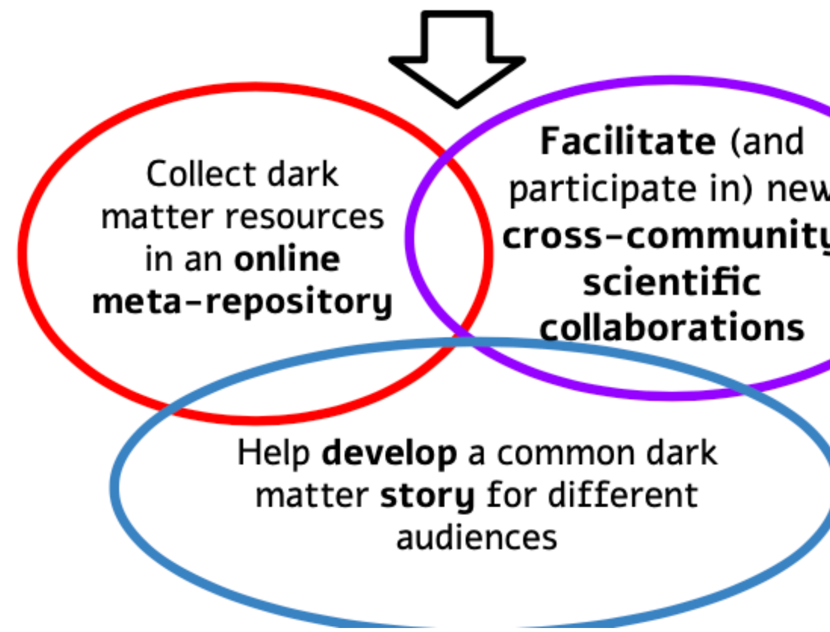
The best region to find dark matter is the one where more techniques and ideas can **discover** and **explore** DM!

⇩

After the European Strategy Update process and during a joint ECFA/APPEC/NuPECC (JENAA) meeting, a number of DM researchers met with similar questions:

E.g. "what are your assumptions?" "why do you use this technique?" "how will findings in your DM research impact my DM research?" "where can we meet and discuss this topic in depth after this meeting?"

We realized that there was **no common platform** for these discussions or for resource sharing → we decided to start developing it, with three interconnected objectives



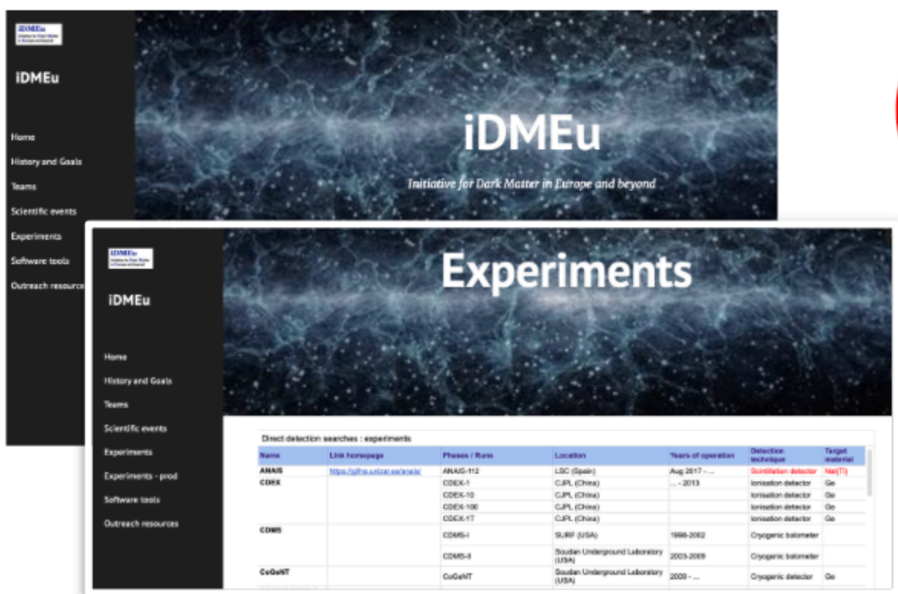
More about iDMEu (following yesterday's discussion)

Three connected **iDMEu objectives**

Note: iDMEu is intended as a platform that brings together **existing/future** community efforts

iDMEu enables finding **synergies** and highlighting the **complementarity** of different dark matter communities by developing a **common platform** to:

Domain and preliminary website: iDMEu.org



Work in progress: tables of past/present/future DM experiments

- Collect dark matter resources in an **online meta-repository**
- **Facilitate** (and participate in) new **cross-community scientific collaborations**
- Help **develop** a common dark matter **story** for different audiences

Today and tomorrow's **community talks**
+
Tomorrow's **breakout sessions**
+
Wednesday's **closing session**

Wednesday's **outreach session** (with a hands-on component)

Gabriella Szabó (Bachelor student, Lund University, Sweden) — Romane Kulesza (Bachelor student, PSL University, Paris, France) — Tom Laclavère (Master student, Université de Paris, France)

Created by **curators:** students doing an internship on collecting info & learning about DM → contact us if interested!

2

Link to kick-off meeting (with recordings)

Mailing list: sign up on e-groups iDMEu-jenaa-eoi@cern.ch

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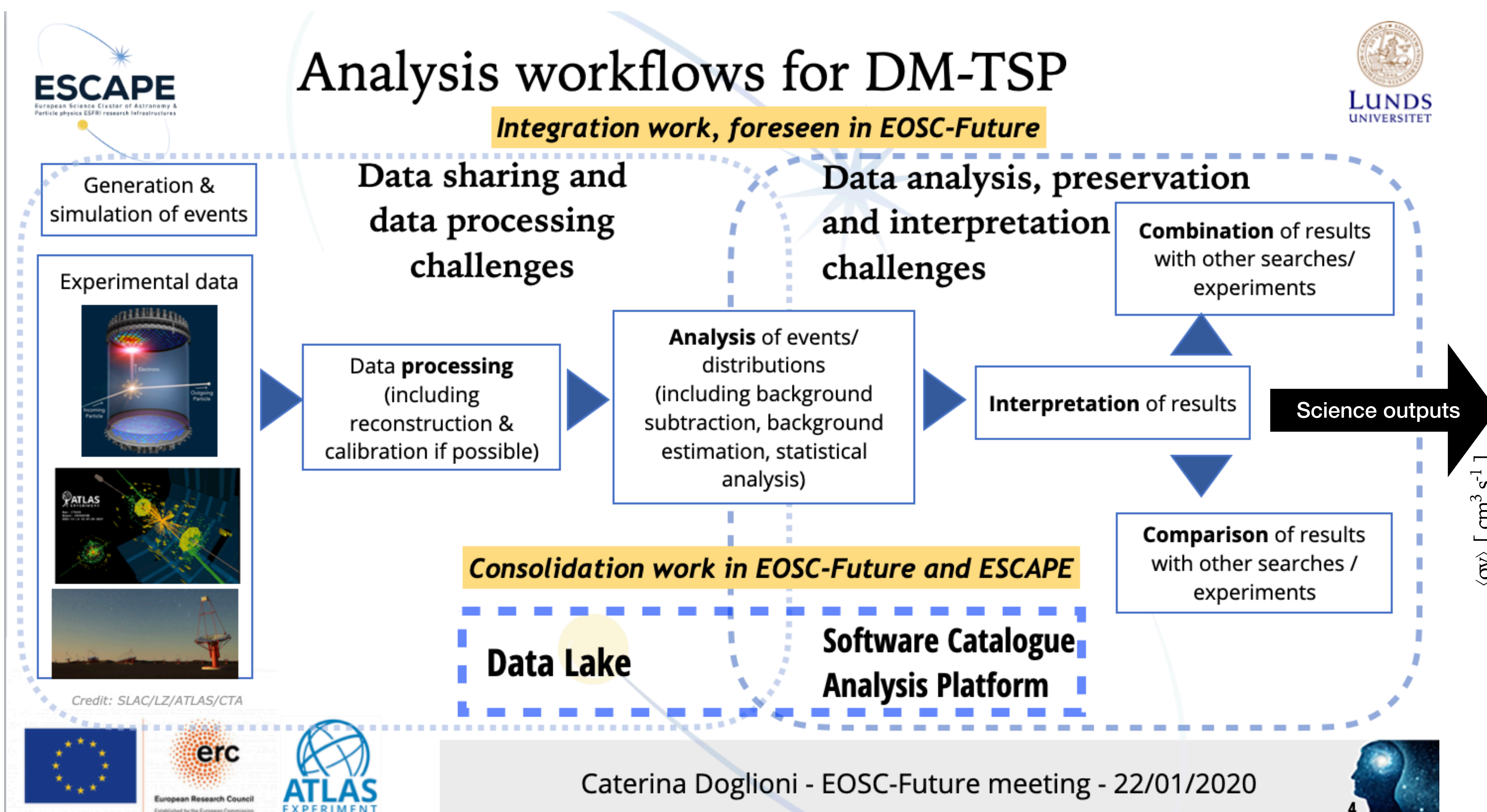
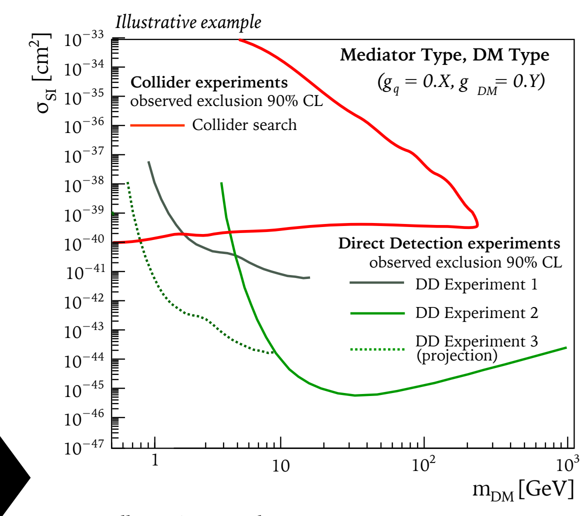
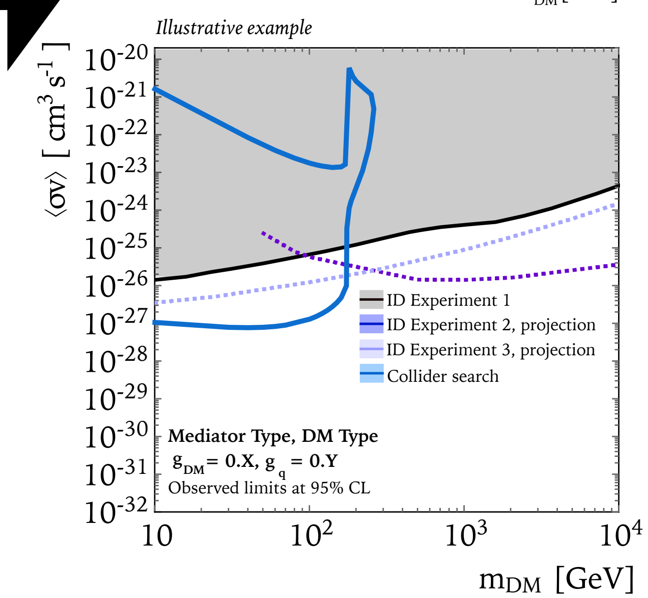
More about the Dark Matter Test Science Project in EOSC-Future

- Implement open and reproducible end-to-end analysis workflows on a common infrastructure
  - Using ESCAPE services, see https://projectescape.eu, to serve as stepping stone for European Open Science Cloud
- **DM Test Science Project (TSP):** take 5 use cases included in ESCAPE
  —> 5 postdoc positions funded by INFRAEOSC-03 open here
  - Another parallel TSP for Extreme Universe (focused around gravitational waves)



Direct detection plane





Indirect detection plane